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**LANDSLIDE CLASSIFICATION AND STUDIES OF TAIWAN**



By  
**Ted C. Sheng**

Taipei, Taiwan, China  
December 1966

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## FOREWORD

In the upstream watersheds of Taiwan landslide has long been a major critical problem. It not only threatens the reservoirs and other public installations below but also aggravates flood damages and endangers human lives and properties. The study of landslides is essential for better understanding of their phenomena and causes so that possible treatment and correction measures could be applied effectively.

The classification of landslides is only the first step toward landslide study and treatment. This new classification, based primarily on immediate causes and treatment standpoint, has been used satisfactorily in many watersheds of Taiwan. However, further improvement and development are needed. More landslide study and research are also necessitated in the future.

Mr. Ted C. Sheng's thesis offers a practical example of landslide classification and study. His recommendations on slope stability potential, treatment and correction, and future research needs are inspirable. The long chapter of "Review of Literature" provides valuable information to persons who are interested in this subject while the references are not all available in Taiwan.

Finally, thanks are due to the Colorado State University for granting the permission of publishing this thesis originally entitled "Development of Landslide Classification for Mountain Watersheds of Taiwan, China" which Mr. Sheng fulfilled partially the requirements for his Degree of Master of Science in watershed management at the said University in December 1965.

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## ABSTRACT

Massive landslides present a very serious problem in the mountain watersheds of Taiwan. A new and simple landslide classification scheme has been developed. This classification can be used for classifying landslides on either artificial or natural slopes. It should prove particularly valuable for reconnaissance type of landslide survey. Both field investigation and air-photo interpretation and delineation can easily apply or adapt it. The scheme mainly depends on immediate causes of landslides such as runoff concentration, stream cutting, seepage, road excavation, cultivation and geologic causes. Other environmental factors like slope, aspect, elevation, land use, soil and rock type are included in the scheme. Landslide size, volume, stability and treatment needs are also considered.

Six hundred and thirty landslides in three mountain watersheds have been investigated. Their occurrences in relation to immediate causes and environmental factors are analyzed and discussed. Statistical methods and computer calculations were employed in part of the analysis.

Recommendations have been made for possible treatment and correction of landslides. Landslide potential classification is suggested for further consideration and development. Future research on landslides is also recommended.

This classification has been used satisfactorily in humid and rugged upstream watersheds in Taiwan. However, improvement and development will be needed when more experience and research findings are obtained.

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## INTRODUCTION

Taiwan is a tobacco-leaf-shaped island with a central range of mountains running north to south serving as a backbone. Approximately two-thirds of Taiwan is steep mountainous country with 30 peaks over 3,300 meters in elevation. The entire island is severely dissected by 150 short and steep streams most of which originate in the central range and run either east or west to the sea.

Due to its geologic youth, abundance and high intensity of its rainfall, and to the common occurrence of earthquakes, Taiwan suffers from severe landslides in its mountain watersheds. Landslides not only contribute tremendous quantities of sediment to the streams and reservoirs below but also aggravate flood damages and claim a heavy toll in human lives in the densely populated island. After a visit in the summer of 1963, Dr. Robert E. Dils of Colorado State University reported (1964) that the most significant watershed problem in the mountain-forest zones of Taiwan is that of massive landslides.

### Extent of Landslides

There are presently no exact figures

on the total area and distribution of landslides in Taiwan. However, from some sources of information such figures can be estimated. According to Chou (1960) a landslide survey was conducted in six main watersheds in 1935 by N. Yoshei. A total of 13,870 hectares of landslides was reported as the result of that survey. The distribution was as given in Table 1-1.

In 1956, an island-wide land use and forest resources survey was completed. Statistics from this survey showed that a total of 117,400 hectares should be classified as "denuded, unplantable." According to the definition, "denuded, unplantable" is "Bare lands such as landslides, unstabilized alluvium and bare rocks that are not suitable for planting to trees." Doverspike et al. (1956) noted, "Because of the steepness of topography and the violent nature of the rivers, certain areas already are beyond the possibility of economic repair and reclamation. In 1955, 117,400 hectares were placed in this class."

Although there is no detailed breakdown of this "denuded, unplantable" to show the exact area of the slides, an

*Table 1-1. Landslide Areas in Six Watersheds of Taiwan  
(Investigated and Reported in 1935)*

Location	Name of Watershed	Area of Landslide (Hectares)
Central Taiwan	Choshui River (upper reach)	3,980
	Chen-yu-lan Creek	3,390
	Wu River	1,570
	Ta-an Creek	990
Southern Taiwan	Tsengwen Creek (upper reach)	770
	Hsia-tan-shui Creek (upper reach)	3,170
Total		13,870

Source: Chou, H. Soil and Water Conservation. 1960

estimation may be made from another report of the same survey. Hsia (1957) participated in the non-forest part of this survey and noted that the "denuded, unplantable" land occupies almost the whole class of non-forest problem area class V. The definition of problem area class V is "Denuded lands which lack sufficient soil to support forest cover. Only by very expensive uneconomical measures can such lands be made productive." Under class V, there are 39,500 ha. of land above the elevation of 600m. which is generally considered to be in the region of mountain watersheds. Thus, this 39,500 ha. of class V land might be a close estimation of landslide areas in the watersheds of Taiwan. Another finding revealed in the same report is that 44,000 ha. of "denuded, unplantable" land lie in the national forest. In Taiwan, the national forest covers almost all of the mountain range. Most of the "denuded, unplantable" area in this region is believed to be in the form of landslides rather than in the "unstabalized alluvium" of the lowland valleys. It is, therefore, safe to say that the active landslide area in the mountain watersheds of Taiwan is about 40,000 ha. The other 77,000 ha. under the same category, "denuded, unplantable," may be the areas influenced or produced by landslides.

### Significance of Landslides

Landslides are frequently disastrous in densely populated Taiwan. They also threaten or endanger the national economy. Numerous examples of this can be cited, however, only a few are mentioned here.

According to Chu (1961) several hundred hectares of landslides at the headwaters of Mukua Creek at east Taiwan caused an aggradation of 20 m.

in the downstream reaches and a complete burying of the Tungmen Powerplant complex in 1948. The plant had a capacity of 29,000 kw. and has since been rebuilt underground. A recent survey of the Mukua Creek watershed reveals that there are 3,400 ha. of landslides in this 46,800 ha. of watershed and the river bed from the powerplant to 7 km. downstream has been aggraded at an average of 13 m. in a period of twenty-two years (1941 to 1963).

Sheng and Koh (1965) reported that hundreds of landslides created by one typhoon in 1963 had deposited 19.5 million cubic meters of silt in the Shihmen Reservoir, a 100 million U. S. dollar project in Northern Taiwan, only one year after its completion. This amount of silt is an equivalent of one-third of the reservoir dead storage provided for 80 years (see Plate 1-1).

In the summer of 1959 a mud-flow type of landslide occurred in the foothill zone of Changhwa Hsien in Central Taiwan. It caused a death toll of 69 and left 1,500 homeless due to the burying of the village. At the upstream area of Ching-shui Creek a natural reservoir of 150 million cubic meters was formed by the deposition of 4,800,000 m<sup>3</sup>. material produced from a landslide due to the earthquake of December 1941. Unfortunately the natural earth dam collapsed in May 1951. In the flooded area, 11,130 persons were affected, 134 were killed. Five hundred houses were completely destroyed and 3,116 ha. of croplands were damaged. The total loss was estimated at 17 million New Taiwan dollars.\*

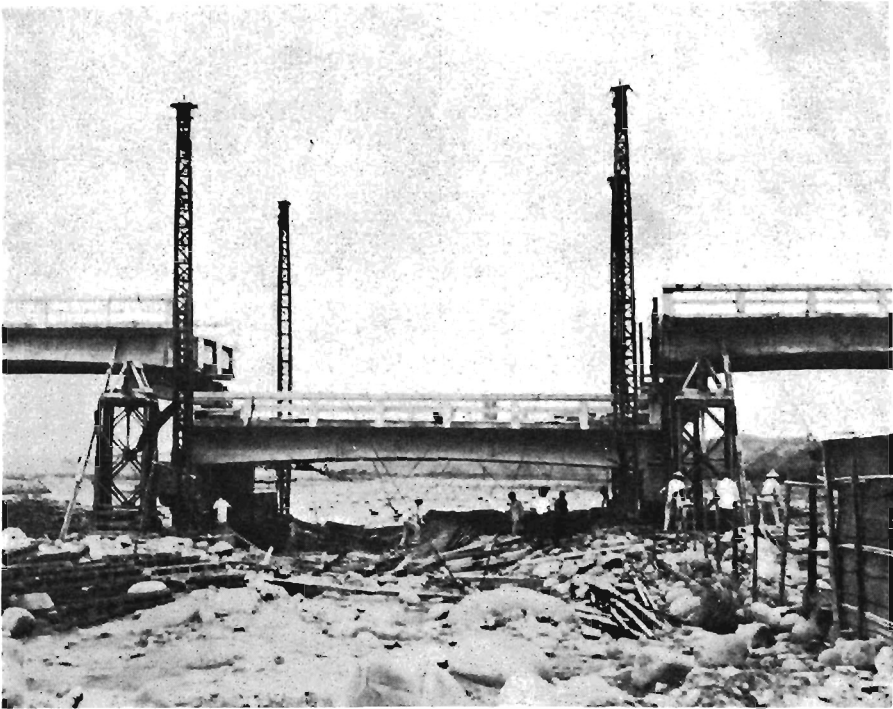
The streams of Taiwan carry tremendous sediment loads. The high sediment content is mostly a result of

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\* One U. S. dollar to forty New Taiwan dollars



*Plate 1-1. Heavy siltation occurred at the tail water of the newly completed Shihmen Reservoir. This was due to Typhoon Gloria which created hundreds of landslides in the watershed in September 1963.*



*Plate 1-2. A bridge on Tou-wu Creek of Northern Taiwan is being raised 2.5 meters because of the aggradation of river bed by sediment. This bridge was originally constructed in 1957.*



*Plate 1-3. The Central Cross Island Highway created many landslides along its course in steep mountainous country.*

landslides and stream bank cutting. In the newly surveyed Tsengwen watershed of southern Taiwan it is reported that 83 percent of the annual sediment discharge is from landslides and stream bank cuttings. The Choshui (Muddy) River above Chi-chi carries 60,000,000 metric tons of sediment annually to the lowlands and the sea from some of its slide-prone upstream tributaries. The total basin above is 2,300 km<sup>2</sup>. producing almost 26,000 metric tons of sediment per square kilometer a year. As reported by the Water Resources Planning Commission of Taiwan (1957), the Muddy River leaves an average of 1,060,000 m<sup>3</sup>. of silt a year in irrigation ditches. It costs 3,200,000 New Taiwan dollars to clean them annually.

Flood damages in Taiwan are undoubtedly aggravated by the heavy sediment loads brought primarily from the landslide areas in the mountain watersheds. The aggradation of river beds (see Plate 1-2) usually contributes further to the inundation, washing, and burying of land in the adjacent area. According to Chou (1960), of the total land damaged by floods at the lower reaches of 13 streams from 1910 to 1932, 22,000 ha. were buried under sand and gravel. The Taiwan Agricultural and Forestry Aerial Survey Team (1950) also reported that a total of 29,000 ha. of agricultural land was buried during the August 7 flood of 1959. This buried lands made up 92 percent of the total seriously damaged agricultural land in that flood.

In recent years new highways have been constructed across the mountains and more lands in the mountainous country have been subject to intensive use due to population pressure. Consequently these activities are causing additional landslides. The cross island highway in

central Taiwan, for example, has created numerous landslides along its course (see Plate 1-3). Since its completion in 1958, landslides have blocked the road throughout almost the entire typhoon season from June to September each year.

### Landslide Classification Needs

The Island of Taiwan is crossed by the Tropic of Cancer in the south and has the characteristics of tropical and sub-tropical climates. The average annual rainfall is 2,500 mm. and in some mountain regions the rainfall is as much as 5,000 mm. a year. Because of its geographic position, typhoons hit Taiwan at an average of 3.7 times annually. With a velocity of 20 to 40 meters and sometimes 60 meters per second, they are usually accompanied by heavy rains, causing severe landslides and catastrophic flood damages. In some places, 1,000 mm. a day was resulted. Local shorter storms occur throughout the island during the summer. It is not unusual to record rainfall intensities up to 100 mm. per hour or more.

Morphologically speaking, the valleys in the mountainous areas of Taiwan are at their youthful stages. The stream gradients are steep and valley sides are V-shaped with little or no floodplain development. The mountain slopes mostly exceed 20 degrees, and 35 degree to 45 degree inclinations are not uncommon.

The mountains are composed chiefly of sedimentary rock formations of which a moderate part has been subject to different grades of metamorphism. They are highly unstable and disintegrate readily. Along the Central Range the principal rocks are soft slates and deeply weathered schists. On the lower part of the mountain regions, well fractured

sandstones, gray shales, and alternating beds of sandstone and shale are dominant. Soils in the high mountains are shallow and stony. Red-yellow podzolic soils and latosolic soils occur at the lower elevations. Here abusive cultivation is common.

In addition, Taiwan lies on the circum-Pacific earthquake belt. There are approximately 300 perceptible tremors and 1,000 imperceptible shocks each year. Earthquakes undoubtedly add to the instability of the mountain slopes.

All the above-mentioned factors, consequently, contribute to severe erosion and active landslides in the upstream watersheds of Taiwan. Although forests have covered most of the mountains, the production of sediment has never been decreased.

Sedimentation is a major problem when storage reservoirs or other water resources projects are contemplated. In 1958, an island-wide water resource study was completed. According to the report submitted by the Engineering Office of Clyde C. Kennedy entitled "Water Resources Planning in Taiwan" (1958), the identification of sources of sediment and the development of control measures are essential to water resources development projects. In its section on conclusions and recommendations, the report stated:

"Knowledge of a sediment production and its control will be a most important factor in storage development in Taiwan. Hasty development of storage sites before an adequate economic life for the reservoir can be assured is not recommended."

This report also realized that landslide is one of the major sources of sediment supply on the island and called for "more investigation."

Taiwan has proposed the development of water resources in two of its biggest basins in the central area, the Choshui (Muddy) and Wu (Black) River Basins, for nearly ten years. Many survey and planning projects have been carried out, some of them with the assistance of the United Nations Special Fund. In view of the serious sediment problem in the upstream areas, recent attention has been given to the investigation of sediment source areas, especially to the existing slides. Potential slide conditions and possible upstream improvement measures for the proposed reservoir sites must be evaluated. The contractor of the present planning project, Acres International Limited, wrote to the Project Manager of the United Nations Special Fund, Mr. H. N. Walker, on November 11, 1964, stating the purpose of the survey as follows:

"We would define the initial purpose of the survey as being the identification and quantitative assessment of the principal sources of sediment in the drainage basin, and the correlation of these sources with the sediment load in the river. The ultimate purpose would be the formulation of concrete proposals for the improvement of existing conditions."

As mentioned before, Dils(1964) was deeply impressed with the severity of landslides in Taiwan. In the chapter "Research Needs and Recommendations" he states:

"A major problem at high elevations is that of the massive landslides. In most cases it is felt that these slides are geologic in nature and that control is uneconomical if even possible. However with new highways under construc-

tion and with additional forest harvesting anticipated a study of landslide conditions and causes is appropriate. A survey of geologic, topographic, soil and vegetative conditions on areas subject to many slides could provide very useful guides to future highway location and to safe logging areas. A team approach (including a geologist, a soil scientist, and a forester) would be necessary for such a survey, and

the ultimate development of a landslide classification."

From the foregoing it is obvious that landslide classification and study are urgently needed in Taiwan before better watershed and water resources projects can be developed. It is also important to note that the ultimate goal of such classifications and studies is to provide the basis for future treatment, improvement and management.

## REVIEW OF LITERATURE

### Definition of Landslide

Many definitions have been offered for the term "Landslide". However, there has been no general agreement among scientists. In everyday language, the word "Landslide" implies all kinds of downward movement of the land. In scientific fields, it has both a narrow (or restricted) meaning limited to certain types of mass movement, and a broad sense which includes all the related phenomena. Consequently, different people have different concepts about the speed, the material and the type involved in landslides, hence their definitions are different.

Sharpe(1938)in his book "Landslides and Related Phenomena" pointed out "Many definitions of landslide have been presented in the literature and there is little agreement as to the exact meaning of the term." He suggested, "It will be best to define landslide simply as the perceptible downward sliding or falling of a relatively dry mass of earth, rock, or mixture of the two" (this is his definition of landslide in the restricted sense). He also realizes that landslides usually have sufficient water to aid in lubricating a slip surface and that the movement is from rapid to moderately rapid.

Terzaghi (1950) divided mass movement mainly into "creep" and "landslide" with a range of speed as follows:

"The term landslide refers to a rapid displacement of a mass of rock, residual soil, or sediments adjoining a slope, in which the center of gravity of the moving mass advances in downward and outward direction. The velocity of the masses involved

in a typical landslide increases more or less rapidly from almost zero to at least one foot per hour."

Scheidegger (1961) also states the velocity of the moving mass increases from zero to at least one meter in three hours.

Fukuoka (1953) of Japan noted, "Generally speaking, a landslide is defined as a slope movement that has a velocity of 1.0-0.001 mm. per day (commonly 10.0-0.1 mm. per day)."

Other American geologists and engineers such as Thornbury (1954), Schultz and Cleaves (1955), and Leet and Judson (1958) follow primarily the definition of Sharpe and agree that a landslide involves a relatively rapid movement of the mass, with no numerical value mentioned. However, Hennes (1936a), Eckel (1958), Baker and Chieruzzi (1959) failed to mention speed in their landslide definitions.

Of the sliding material Sharpe considers that landslides consist of "earth, rock or mixture of the two." Varnes (1958), in the U. S. Highway Research Board report, also mentions that landslide includes all slope-forming materials—natural rock, soils, artificial fills, or combinations of these materials. Leet and Judson (1958) express opinion that "some landslides involve only the unconsolidated debris lying on bedrock, while others involve movement of the bedrock itself."

According to a Russian geologist Popov (1963), "N. F. Pogrebov has defined mass wasting in the broad sense as movement of a rock mass downward under the influence of gravity." Nakamura (1955) of Japan separates landslide from landcreep in stating that landcreep

includes only the movement of debris and soils whereas landslide includes bed rocks, or debris and soils.

The type of landslide is more complicated. Detailed classification and description will be discussed later. At present, however, the writer wishes to discuss only its general scope.

"Landslide" is sometimes used as a synonym for "mass movement" or "earth movement." In the broad sense, as mentioned previously, it may involve all kinds of displacement phenomena. According to the Encyclopedia Americana (1965), landslide is expressed as "the displacement of a mass of earth material (soil or loose rock) by gravitational forces." The Collier's Encyclopedia (1965) explained, "in its restricted sense the term landslide is used only for those mass movements that slide over the underlying rock. Landslides may be as slow as soil creep, or they may be swift and destructive." In the Encyclopedia Britannica (1964), the definition is somewhat similar that the downward mass movement of earth or rock on unstable slopes includes many forms resulting from different conditions. As we can see, so far, the term "landslide" has been used loosely in common language.

Even in scientific fields and in the restricted sense, landslide has been defined in different types by different persons. Sharpe (1938) divided mass movements into four groups one of which is landslide. He further subdivided landslide into slump, debris-slide, debris-fall, rockslide, and rockfall. In his classification, "flows" and "creeps" are under different groups. Varnes (1958) classifies landslides into three major types: falls, slides, and flows. This classification has been adapted by the Highway Research Board of the United

States and many other persons. He has also excluded "creep" as one type of landslide but has included "flows."

Another approach to the problem of defining the scope of landslides is shown by Leet and Judson (1958) and Pearl (1963). They divided mass movement into slow and rapid forms. Under rapid movement they listed landslides which consist of slump, rockslides and debris slides. No "flows" are included.

In Japan, T. G. Wakeymizu divided mass movement into "landslide" and "landcreep" and then subdivided "landslide" into "landslide proper" and "landslip." The "landslide proper" includes rockfall, earthfall and large scale landslide. No "creeps" and "flows" seem to have been included. Although his general division has been accepted in Japan ever since, the real division between landcreep and landslide is still not clear (Noguchi 1963).

Terzaghi (1950) has also listed the main differences between landslides and creeps, but he pointed out that no sharp boundaries between these two groups of slope movements could be drawn.

Although in early Chinese literature there has been phrase like "mountain avalanching and earth cracking," the modern translation of "landslide" is rather confusing. Under officially published terminology by the Ministry of Education, three different translations are used. In the "Terminology of Forest Science" the translation is "mountain avalanche" which is rather traditional and classic. "Slope failure" has been adapted as a translation in the "Terminology of Civil Engineering" whereas "earth avalanche" is used in the "Terminology of Hydraulic Engineering." Due to such differences in translations, the true scope or meaning of landslide has never become scientifically clear.

Regardless of all the complexity, there are at least three general charac-

teristics common to all landslide definitions:

- (1) They are land masses including either soil, rocks or a combination of the two.
- (2) They involve displacements from the original site by gravity.
- (3) They are downward movements.

In Varnes' definition for the Highway Research Board report (1958), outward movement is also included. It is the writer's opinion, however, that the ultimate result of outward movement is still downward movement. Consequently, the definition of landslide in the broad sense, may be given as: "The downward movement of a land mass." In a more restricted sense some words may be added to the former sentence: "The relatively rapid downward movement of a land mass from a slope."

### **Causes of Landslides**

The causes of any landslide movement can be very complex. However, there must be one leading factor which dominates the others to initiate the slide. This may be referred to as an immediate cause, direct cause, or major cause. As Baker (1953) indicated, "almost all landslides result from a combination of causes, with one factor being finally dominant." Scheidegger (1961) in his "Theoretical Geomorphology" stated:

"Any attempt at a theoretical explanation of landslides has to account for the fact that slides may occur on slopes that have been stable for a long time, sometimes for many thousands of years. Thus if a slide occurs, there must have been an agent which caused a decrease of the stability of the slope so as to make it collapse. In every landslide, there must be therefore a

direct mechanical cause."

Zolotarev (1963) of Russia also points out that geological processes are combined and interconnected, however, it is possible to distinguish the one dominant process which determines the development and features of a slope in some definite segment of time. On most slopes during each stage of development, other processes play a subordinate role.

In the classic landslide literature similar statements can be found. According to Howe (1909), Heim had the opinion that a distinction should be made between the remote and the immediate causes. Conditions favorable to landslides may continue for long periods and yet no movement may take place until some event, such as an unusual amount of rainfall or an earthquake, gives the the touch necessary to start the unstable mass on its downward movement.

Holmsen (1953) states that in speaking of the cause of landslip one usually means the immediate cause—that is to say, the cause of "the initial slip." Any effort to counteract possible landslips therefore implies attempting to prevent the initial slip.

#### *I. Fundamental Concepts*

According to Scheidegger, up to the present little is known with regard to the actual dynamics of a landslide from a theoretical standpoint. Probably, as pointed out by Forbes (1947), no two slides are the result of conditions exactly alike. The model study and soil mechanics approach are usually on idealized materials and are not quite applicable to the complex geological structure and soil conditions of the field. However, some general principles are still worth mentioning.

From the standpoint of geologic

time, it may be said that no slope is permanently stable. Landslide is rather a part of the geomorphologic process which shapes the land form of the earth. People are more concerned about sudden and catastrophic changes than with slow and continuous movements. The reason we study the causes of landslides is to find the root of trouble. Once that is determined, man can do something preventively or correctively to keep the land stable for a desirable period of time.

Many conclusions have been drawn that landslides resulted from either a decrease in shearing strength or an increase in shearing stress. Leopold et al. (1964) stated that this unbalanced condition may be brought about by (a) an increase in the weight of the overlying material, (b) a decrease in the resisting mass, and (c) a decrease in shear strength of the material itself. Terzaghi (1950) explained "as long as the shearing stress in the material beneath a slope is smaller than the fundamental shearing resistance of the material, the slope is at rest." The general expression of safety factor is as follows:

$$\text{Safety factor} = \frac{\text{resisting movement}}{\text{driving movement}}$$

If the value of the safety factor is greater than one, the resisting movement is larger than the driving movement and the slope is safe. If it is smaller than one the slope will fail. Popov (1963) also explains that the principal cause of sliding is the disturbance of equilibrium of the mass on slopes when these slopes acquire a steepness that is greater than the angle of repose for the particular rocks forming the slopes.

All landslide correction methods, therefore, rely upon the restoration of the equilibrium.

## II. *External and Internal Causes*

The causes of landslides are numerous. Howe (1909) firstly grouped them into two big categories, namely, internal cause and external cause. Terzaghi (1950) further explained that "external causes" are those which produce an increase of the shearing stresses at unaltered shearing resistance of the material adjoining the slope. They include slope steepening or heightening by stream erosion or man-made excavation, deposition of material at the upper edge of slopes, and earthquake shocks. "Internal causes" are those which lead to a slide without any change in surface conditions and without the assistance of an earthquake shock. The most common causes are an increase of the pore-water pressure and progressive decrease of the cohesion of the material by chemical or physical weathering. Terzaghi also pointed out that between external and internal causes are those due to rapid drawdown, to surface erosion, and to spontaneous liquefaction.

Panyukov (1963) of Russia has somewhat different ideas. He said: "The state and deformation of a slope are the consequence of the mutual effect of the internal interrelated processes acting both on the surface of the slope and its base (slope wash, stream erosion, undercutting, etc.) as well as within the mass of rock itself in the slope (weathering of the rocks, filtration pressure of ground water, changes in the stress state of the mass of the slope due to change in the geometry height and steepness, changes in the physical state and deformability of the rocks, etc.)" In other words, Panyukov considers that a deformation is caused by both external and internal actions.

However, as mentioned previously the important cause is the one which

dominates all others. It is not the writer's intention to make a purely academic analysis of the theory involved in all kinds of causes. To distinguish between internal and external causes is a painstaking work of theoretical nature. This paper deals primarily with some important causes which occur in a humid and sub-tropical climate zone like Taiwan.

### III. *Immediate Causes*

As mentioned before, the immediate cause is the one which initiates the landslide and which therefore deserves more attention. Generally it can be divided into natural and human factors as suggested by Holmsen (1953). In addition to gravity—which is the cause of every landslide and is hereby excluded as an immediate cause—rain and runoff, streams, and groundwater may be the universal causes of landslides. Earthquakes and wind sometimes are also important but their influences are difficult to pinpoint. Among the man-made causes, road excavation and mining may be the most significant. Logging, farming, grazing and fire may have some effects on sliding.

#### 1. Rain and Runoff:

Landslides are closely associated with heavy rainfall. In the United States, studies of landslides have reported that many slides were entirely created by storms. Flaccus (1958) studying the landslide history and occurrence dates at White Mountain, New Hampshire, indicated, "All slides (135 slides) for which dates to the day are available occurred associated with heavy rain." None had occurred in the months of snow melt and spring rains. Hack and Goodleft (1960) reported that a seven inch storm in the summer of 1949 caused 100 landslides in the densely-forested Little River Basin of the Central Appalachians. They also noted

"sliding of debris during torrential rains as an important mechanism in the erosion of these areas." In west Virginia, Scheffel (1920) found "slides are much more frequent in seasons of abundant rainfall than in seasons of light fall." A Florida landslide, reported by Jorden (1949), was caused by a sixteen inch rainfall. In this instance 146,000 cubic yards of earth broke away from a gentle slope (not exceeding ten degrees). Putnam and Sharp (1940) reported that the runoff and other phenomena associated with heavy rains produced many significant changes in the landscape of Southern California during the winter of 1937-1938. Landslides were set in motion and great quantities of material in areas of weathered bed rock were moved by earthflows. In Central California, Kesseli (1943) also reported, "The relation of disintegrating soil slips to rain is quite apparent. The fresh scars are seen only during the winter rainy season and are particularly conspicuous shortly after heavy rains lasting a number of days." In early landslide investigations in the San Juan Mountains of Colorado, Howe (1909) realized that excessive rainfall was one of the important external causes responsible for landslides.

Koide (1955) and Nakamura (1955) of Japan also reported the close relation between storms and landslides. Sheng (1960) has reported that after the storms of August 7, 1959 numerous landslides occurred in an extensive area of central Taiwan.

Surface runoff produced by intense and prolonged rainfall is a powerful agent in causing erosion as well as landslides. Scheidegger (1961) stated that "The most important agent in slope development is erosion caused by water flowing over a slope." Leopold et al. (1964)

expressed a similar opinion in saying "perhaps the most ubiquitous process occurring on hillslopes is erosion and transport by running water." Several Russian scientists feel that both surface and ground water are the most important factors in causing landslides. Panyukov (1963) stated that the special significance of surface and ground water in the development of physico-geologic phenomena had been emphasized by many investigators. Pogrebov pointed out that mass movement was commonly associated with the activity of surface and ground water.

The mechanisms involved in the creation of landslides by percolating rainfall offer material for interesting argument. Many geologists and engineers believe that the percolating water acts as a lubricant to generate slides. Terzaghi (1950), however, argues that there is sufficient water in any earth mass to produce the necessary lubrication especially in humid regions. Terzaghi considers the effects of water in the earth mass as follows: (1) it eliminates the surface tension of soils and thus reduces cohesion, (2) it increases unit weight of the soil, (3) it removes soil binding materials by solution, and (4) it causes a rise in the piezometric surface, which, in turn, increases the porewater pressure and decreases the shearing resistance of the soil.

Forbes (1947) also believes that the weight of the added water alone may overstress the material and increase its instability; the fluid may reduce cohesion and friction within the mass; the ground water level may thus rise, causing increased hydrostatic pressure with resulting uplift forces and blowout; and the absorbed moisture may create geochemical changes that weaken and swell the soil particles so that they cannot support loads.

The concentration of surface runoff in the depressions of a slope may cause tremendous erosive force. It triggers landslides by deepening and widening of the gullies.

## 2. Stream Cutting:

Stream plays a very important role in shaping landform. As Penck noted many years ago, stream and hillslope processes provide the central theme of geomorphology. It is the writer's impression that in areas of steep topography and high rainfall even hillslopes are at the mercy of stream processes. Scheidegger (1961) pointed out "some of the most striking features upon any landscape are caused by the work of rivers." Popov (1946) states that the steepness of the slope undermined by river or sea is the most frequent cause of landslides.

Baker and Chieruzzi (1959) studied the regional concept of landslide occurrence in the United States pointing out that an interesting observation relative to apparent physiographic discrepancies is the presence of landslides near major water courses. After an extensive study of hundreds of landslides in the United States, Liang (1952) found numerous slides occurring along valleys strategically attacked by rivers. He found slumps to be common at the point of maximum curvature in a bank of unconsolidated materials.

In Norway, Holmsen (1953) reported that most of the greater landslips of historical age appeared to be caused by river erosion. Krynine (1960) reported landslide investigation condition in Russia and indicated that an important sliding factor was the undermining of slopes by both stagnant and current water, and particularly by waves.

Stream cutting triggers landslides in several ways: (1) by removal of the

support at the toe of the bank, (2) by saturating and weakening the soil mass above normal water level during high flow, and (3) by rapid drawdown of water level during flood recession.

### 3. Groundwater and Seepage:

Previous discussion has mentioned the importance of groundwater to landslides. Forbes (1947) indicated that all manner of groundwater occurrence, movement, and pressure phenomena are involved in generating slides. Often groundwater characteristics are the principal generating factors, especially when large bodies of material are involved. Root (1953) investigated California landslides and found that groundwater acted in two ways to induce slide movements. First, the weight of a soil mass increased appreciably as the soil becomes wet, thus adding to the driving force tending to cause movements. Second, and of even greater importance, the presence of water resulted in a reduction in shear strength of the soil. Bjerrum (1955) studied the stability of natural slopes in "quick clay" in Norway and Fukuoka (1961) reported on a large slide in Ishikawa Prefecture, Japan. Both considered groundwater to be the major contributing factor in the occurrence of slides in their respective areas

of investigation.

Hennes (1936a) illustrates the effect of water table upon the stability of slopes on homogenous material:

"The water table tends to follow, to some extent, the profile of the ground surface. Any such gradient in the water table indicates hydrodynamic stress, which must be resisted by an equal and opposite stress in soil, thus the net effect is to reduce the factor of safety against slip. It is obvious that in the typical situation represented by the sketch (Fig. 2-1) any increase in the height of the water table will be accompanied by a decrease in the stability the slope."

The seepage of water from a slope usually causes instability. Sometimes fragmental material and sand may be completely washed out toward the base of the slope. According to Ward (1945), there are three common seepage conditions which arise in nature and sand slopes. They are: (a) on lands adjacent to tidewater when the tide falls rapidly in comparison with the permeability of the sand, (b) when a sand slope is completely and continuously saturated by heavy rainfall, and (c) where steady groundwater seepage occurs within the slope.

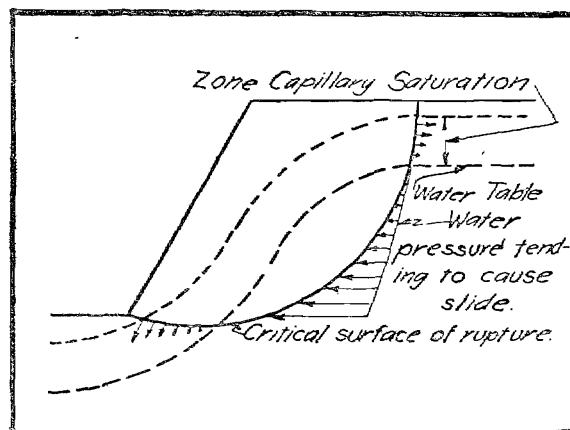


Figure 2-1. Influence of Groundwater Upon Stability of Slopes (After R. G. Hennes 1936b).



shaded areas. The slope in Figure 2-2 (c) tends to fail due to (1) greater water pressure on the potential surface and (2) seepage forces at the toe.

#### 4. Earthquake:

Leet and Judson (1958) show that in regions where there are many hills with steep slopes, large earthquakes are often accompanied by landslides. These slides occur within a zone seldom exceeding 20 to 30 miles in radius, though the largest earthquakes have affected areas with as much as a fifty mile radius. They also point out that only one or two out of all the earthquakes that occur every year are likely to produce such spectacular effects as landslides or the elevation or depression of large land masses.

However, Close and McCormick (1922) reported that a severe earthquake occurred at loess deposits of Kansu Province, China, in December 1920 had created some of the most spectacular landslides on record. The death toll was 100,000 in a sparsely populated area of 30,000 square miles. According to Nakamura (1955), there were 420 recorded instances of landslides accompanying big earthquakes in the history of Japan.

Many investigators (Howe 1909, Forbes 1947, Koide 1955, Suklje 1961, Scheidegger 1961) have mentioned the effects which earthquakes have on landslides. Some consider that the earthquake fractures the rock mass. Some believe that it contributes directly to the sliding. Terzaghi (1950) explained that the earthquake shocks are external causes of landslides because they increase the shearing stress along the potential surface of sliding, whereas the shearing resistance remains unchanged. Popov (1963) reported the use of seismic maps in seeking a regional pattern in the

development of landslides by earthquakes.

Taiwan suffers one destructive earthquake a year on the average. According to Chu (1961) the most serious earthquake on record resulted in horizontal displacement of up to two meters along a fault 20 km in length. In 1941, an earthquake had created a lake in the mountain area of central Taiwan with a storage of 150,000,000 m<sup>3</sup>. by a 200 m. high natural earth dyke. The dam collapsed ten years later, resulting in a disastrous flood with a death toll of a hundred people. Hsu (1955) also reported that on the average there is one earthquake felt each day in Taiwan. It is the writer's opinion that earthquakes may not always directly cause landslides, but they may have effect in shaking, loosening and fracturing the soil or rock mass. All of these will no doubt contribute a factor of instability.

#### 5. Wind:

Although wind plays an equal role with water in soil erosion there is very little literature, so far, regarding its relation to landslides. Hurricanes or typhoons are usually accompanied by torrential rainfall. If landslides occur afterwards, people tend to believe that they are due to the effect of excess rain water, hence it is hard to pinpoint the real effects of winds.

Many scientists neglect the effect of wind on landslides when they list the causes of sliding. However, Sharpe (1938) noted that swaying of trees in the wind is an active or initiating cause of landslides. Scheidegger (1961) also commented that blowing wind may directly affect the shape of the slope.

#### 6. Road Excavation:

Of the man-made causes of slides, road excavation may be the most significant. The Highway Research

Board has made detailed studies on landslides in the United States. According to Baker and Chieruzzi (1959) an estimate of the annual expenditure for landslides on highways in the continental United States would approach 10 million U. S. dollars. Dils (1964), after visiting Taiwan in the summer of 1963, believed that the cross-island highways had caused additional landslides and that the road system leading to logging areas had undoubtedly caused much more damage than the logging. There are many reports and studies about the effects of road excavation and construction on landslides (Baker 1953, Root 1953, Eckel et al. 1958, and Cleaves 1961). Possible harmful effects of road cuts and fills may be summarized as follows:

- (a) Removal of the toe of the slope or oversteepening the cuts in unstable rock or soil.
- (b) Overloading on sloping bedding plane or weak layer.
- (c) Increase of seepage pressure by cut or fill that changes direction or character of ground water flow.
- (d) Exposure of stiff-fissured clay that may soften when exposed to surface runoff.

#### 7. Mining and Other Man-made Problems:

Subsidence has long been recognized in connection with mining operations in soft ground or with shallow workings (Legget 1962). The piles of overlaying material, as reported by Hoffman (1964) of the Ohio Agricultural Experiment Station, are susceptible to sliding and slumping, particularly when they are placed on natural vegetated slopes. Where spoil banks are placed on natural slopes containing weak layers, landslides frequently occur.

Careless logging may cause landslides. As mentioned previously, roads leading to logging areas may even create more hazards than logging itself. Not much literature is available about landslides directly caused by logging. According to Tompkin and Britt (1951), Roberto Almagia has reported a landslide in Italy caused partly by deforestation.

Destructive fire may induce cracks in the rock and cause surface erosion. Friedrich (1955) reported "Avalanches of snow or earth often occur on steep slopes following forest fire." Abusive farming and over-grazing of slope land may result in gully erosion. Both will promote the instability of the slope. Galpin (1940) of West Virginia and Beaty (1956) of California both observed that many landslides occurred in pastures and grasslands and some in cultivated fields.

#### Types of Landslides

Many different materials, speeds, water contents and processes are involved in the real slides, the types of landslides, therefore, are very complicated. People's interpretations, consequently, make them even more complex.

The occurrence of a slide is always in such a short time and is so unpredictable that people can hardly detect its true process. In fact, a rock-fall may start with rock-slides (Sharpe 1938); a creep may develop into a slide (Terzaghi 1950); and an earth-flow may go with a slump (Jordan 1949). Unless people eyewitness the actual movement they could only judge or guess the type from the existing form of slides in front of them.

However, many scientists have attempted to distinguish the types of landslides. The types are so many that with a limited space, this paper could

only review several important ones.

### I. Falls

Falls are probably the most recognizable type of landslides. According to Varnes, in the report of the Highway Research Board, falls occur when "the moving mass travels mostly through air by free fall, leaping, bounding, or rolling, with little or no interaction between one moving unit and another. Movements are very rapid to extremely rapid and may or may not be preceded by minor movements." There are two types of falls introduced in the report namely "rockfall" and "soilfall."

Sharpe (1938) treated the falls as sub-types of landslides. He illustrated that "debris fall" occurs where unconsolidated material drops from a vertical cliff whereas "rockfall" is common in areas over-steepened by rivers, by valley glaciers, or by wave cutting.

Cleaves (1961) simply notes that falls are one of three basic landslide types in which the materials are influenced by the laws governing free-falling bodies, and by mechanical and chemical weathering.

### II. Slides

The term "slides" here is used as a proper group-type of mass movement. Baker and Chieruzzi (1959) briefly described slides as "landslides caused by shear failure along warped or plane surface." They pointed out, "where the shear-surface is reasonable circular in shape (in two dimensions), the movement is called slump, while a movement with an essentially planar slip-surface is termed a block glide." They further explained, "Following the initial shear, if the moving mass disintegrates or acts as a group of individual particles rather than as a unit block, the slide is further subdivided into rockslide or debris slide."

The definition above is somewhat a modification of the Highway Research Board's report. Slides in the HRB report have been defined as "movement caused by finite shear failure along one or several surfaces which are visible or whose presence may reasonably be inferred." Two general headings are used in the said report (1) material in motion not greatly deformed; including "slump" and "blockglide" and "block slump," and (2) material in motion, greatly deformed; including "rockslide," "debris slide" and "failure by lateral spreading."

However, Sharpe (1938) uses the term "sliding" as a synonym of "landslids" and he subdivides it into five subtypes: "slump", "debris-slide", "debris-fall", "rockslide", and "rockfall." His explanation of each type is as follows: (Also see Figure 2-3)

**Slump:** The downward slipping of a mass rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope from which it descends.

**Debris-slide:** Rapid downward movement of predominantly unconsolidated and incoherent earth and debris in which the mass does not show backward rotation but slides or rolls forward, forming an irregular hummocky deposit which may resemble morainal topography.

**Debris-fall:** The relatively free falling of predominantly unconsolidated earth or debris from a vertical or overhanging cliff, cave, or arch.

**Rockslide:** The downward and

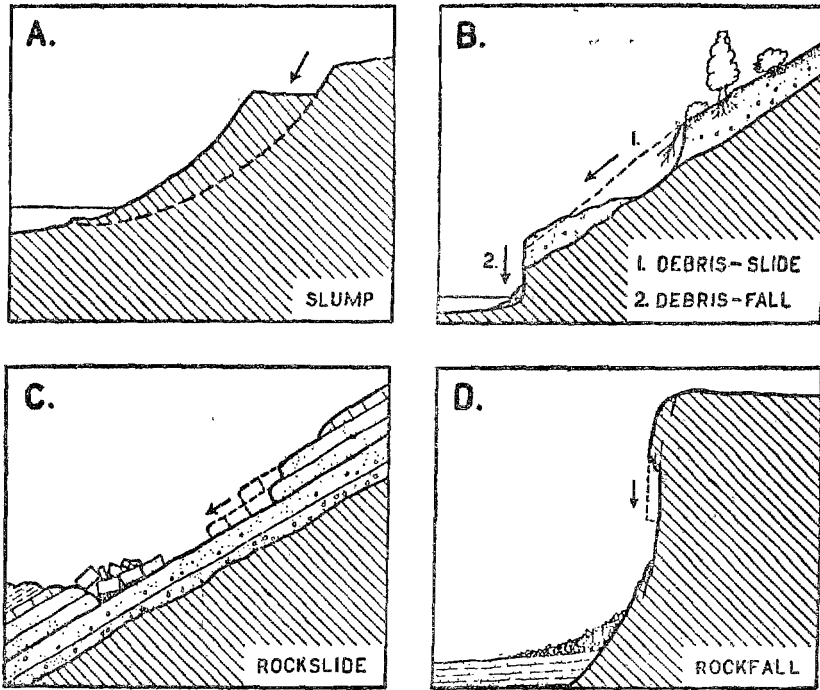


Figure 2-3. *The Five Classes of Landslides.* (A) In slump the mass rotates backward so that the slope of the upper surface of the block is diminished or reversed. (B) A debris-slide may be of any size, may or may not expose bedrock in its course, and often produces deposits resembling morainal topography. Debris-fall occurs where unconsolidated material drops from a vertical cliff. (C) Rockslides may occur on bedding, joint, or foliation surfaces, or any other plane of weakness. (D) Rockfalls are common in areas oversteepened by rivers, by valley glaciers, or by wave cutting. (After C.F.S. Sharpe 1938).

usually rapid movement of newly detached segments of the bedrock sliding on bedding, joint, or fault surfaces or any other plane of separation.

**Rockfall:** The relatively free falling of a newly detached segment of the bedrock of any size from a cliff, steep slope, cave, or arch.

Ward (1945) listed several slide terms and explained them as follows:

**Fragmental slides:** Refers to cohesionless material such as sand, gravel and scree. The failure

of slopes commonly involves a shearing or rolling movement of the surface fragments only, parallel to the slope. Under this type there are four subtypes, namely: (1) dry, (2) partially saturated, (3) saturated, and (4) seepage instability.

**Rockfalls and slides:** Falls resulting from frost action and deeper slides along joints and faults.

**Detritus slides:** Shallow mass slides in predominantly cohesive materials, considerable relative distortion within the

moving mass, mud runs.

Apparently Ward's "slides" do not include "slump" but contain one type of "fall." His other type "rotational shear slips" is somewhat similar to slump as defined by Sharpe and others.

Cleaves (1961), however, simply defines the "slides" as failures in elastic or semi-elastic materials. Sokolov (1963) studied types of displacement in hard fractured rocks in Russia and described "block slides" as those that "develop in massive, inhomogenous, strong, jointed rocks, in which permeable layers alternate with impermeable or semipermeable mudstones or other clayey layers that produce ideal conditions for sliding when they are wet." Bjerrum (1955) and Holmsen (1953) analyzed Norwegian slides in quick clay on gentle slopes and noted that the slides were characterized by their retrograde course, an initial slide being followed by a series of slides in the rear area.

After studying the above definitions and descriptions of slides the writer's general impression is that (1) almost all slides have sliding surface(s) or plane(s) either rotational, straight or irregular, and (2) slides may involve different materials such as rocks, debris, and soils.

### III. *Flows*

"Flows" are as complex as "slides." According to Varnes (1958 in the Highway Research Board report), flows occur when:

"The movement within the displaced mass is such that the form taken by the moving material or the apparent distribution of velocities and displacements resembles those of viscous fluids. Slip surfaces within the moving mass are usually not visible or are short-lived, and the boundary between

moving and stationary material may be sharp or it may be a zone of plastic flow. The material is, by necessity, unconsolidated at time of flow but may consist of rock fragments, fine granular material, mixed debris and water, or plastic clay."

The "flows" are further subdivided by Varnes into two groups and nine kinds. The following is a summary:

Dry flows: Nearly or quite dry.

- (1) Rock fragment flow: Originating into two ways—by volcanic explosion, or by a large rock-slide or rockfall turning into a flow. It has two varieties: rockslide avalanche and rockfall avalanche.
- (2) Sand run: Fluid like motion of dry sand.
- (3) Loess flow: Caused by earthquake.

Wet flows: Requiring water in various proportions.

- (4) Debris avalanche: It may have slump blocks at head. Quite wet and on steep slope. Generally long and narrow and often leaves a serrate or V-shaped scar tapering uphill at the head.
- (5) Debris flow: Contains a relatively high percentage of coarse fragments resulting from unusual heavy precipitation or from sudden thaw of frozen soil.

This flow commonly follows pre-existing drainage way and removes everything in its path. It is favored by deep soil.

- (6) Slow earthflow and (7) Rapid earthflow: The failure follows saturation and the building up of porewater pressure. They may be subdivided into slow earth-

flow and rapid earthflow involving mostly plastic or fine-grained non-plastic material.

- (8) Mudflow: Both earthflows may develop into mudflows when they are wetter. They usually have at least fifty percent sand, silt and clay size particles.
- (9) Sand or silt flow: Occurring mostly along banks of noncohesive clean sand or silt due to scour and repeated fluctuation of water.

It is obvious that the distinction between these nine kinds of flow is a very delicate thing and different people may easily interpret into different results.

Sharpe (1938) included earthflow, mudflow and debris avalanche under the group title of "rapid flowage." He subdivided mudflow into mudflows of semiarid, alpine, and volcanic regions. Terzaghi and Peck (1948) have named a kind of flow, "clay flow", which is somewhat equivalent to the rapid earthflow mentioned by Varnes. Putnam and Sharp (1940) noticed in California that most earthflows have three divisions: (1) at the head are one or more breakaway scarps and a series of cracks, (2) from the middle to the toe is a central division of transported and accumulated material, and (3) the third division is a tongue of semifluid mud that breaks through the toe and extends downslope for a considerable distance.

As a general term, "flow", defined by Baker (1953), "has no plane of failure, but has a more rapid movement than creep and generally results from excessive moisture." Cleaves (1961), however, defined flows as movements which "follow the principles of viscous flow of fluid and semifluid materials." Each definition has its merits as well

as its incompleteness.

#### IV. *Creeps*

"Creeps" are very slow mass movements. In Japan, Fukuoka has reported a creep which began about 100 years ago and which has been moving continuously ever since. However, as indicated by Leet and Judson (1958), creep is usually hard to realize when it is actually taking place. Varnes, Cleaves and many others excluded creep as a type of landslide.

Many studies are underway on landcreep in Japan. The Japanese consider that creeps and landslides are two equally important members of the mass movement family. Koide (1955) explains that there are three characteristic features of creeps. First, they usually occur at certain geologic regions and are less influenced by topography. Second, creeps move with a land mass which usually includes bedrocks. And third, creeps are due to the development of a special kind of clay beneath. Nakamura (1955) described "creep" as a phenomenon of slow and downward movement of debris and soils from slopes.

Sharpe (1938) termed the "creep," "the slow downslope movement of superficial soil or rock debris, usually imperceptible except to observations of long duration." He further named "rock-creep," "talus-creep," "soil-creep" and "rock-glacier creep" under the group type of "slow flowage." Parizek and Woodruff (1957) have criticized Sharpe's definition on creep and suggested "creep is the downslope gravitative transportation of surface and subsurface materials which is imperceptible because of small displacement, slow movement, or quantity of material moved."

Terzaghi (1950) listed the differences between creeps and landslides and subdivided the creeps into two kinds:

Seasonal creep: influenced by thermal expansion and contraction, freezing and thawing and other seasonal processes to a depth equal to or smaller than the depth of seasonal variations in the conditions of the ground.

Continuous creep: below the above depth, the creep can be produced only by the force of gravity unaided by other agents.

Scheidegger (1961) also indicated that temperature changes might indeed be sufficient to cause creep.

#### V. *Subsidence, Solifluction and Other Types*

"Subsidence" is a vertical settling of material with little horizontal motion. Sharpe (1938) has explained subsidence as being a result of coal mining, overloading, earthquakes, and compaction of sediments and solution of salt and gypsum. Thornbury (1954) noted that the common examples of land forms produced in this way are the kettles which form as glacial drift settles over melting ice blocks and the sinkholes of limestone regions. However, in many landslide classifications, subsidence is not considered to be one type.

Solifluction is a production of cold climates and is associated with frost action, freezing and thawing. According to Sharpe (1938), other terms such as flowing slopes, mud-glaciers, and mud-streams have also been used synonymously. "Solifluction" differs from mudflow in its slower and more continuous movement; in that it is not confined to a channel but covers a whole slope; and in the climatic conditions under which it occurs. However, it seldom occurs in sub-tropical climates.

Many other types of landslides have been named as people have found new types which belong to no previous classification. A debris-avalanche type

of slide in Central California has been named by Kesseli (1943) as "disintegrating soil slips" because they leave no irregular hummocky deposit and do not take place in a relatively dry state as in Sharpe's classification. Galpin (1940) termed a local subsoil flow in west Virginia as "blister slips." These kinds of new names will undoubtedly increase as time goes on. The same type may even have different names. Up to this point the writer feels that a standard terminology on landslides is urgently needed.

#### Classifications of Landslides

Many landslide classifications have already been developed but none of them can or should be applied universally. As Terzaghi (1950) has noted, "A phenomenon involving such a multitude of combinations between materials and disturbing agents opens unlimited vistas for the classification enthusiast. The result of the classification depends quite obviously on the classifier's opinion regarding the relative importance of the many different aspects of the classified phenomena." It is true that some types of landslide may occur at many climatic or geographical regions of the world but locally there may still be different types which have never been previously discovered. The varying purposes of landslide investigation may require different classifications. Some may be interested in geologic study; some may require a reconnaissance type of survey; and others may prefer to pay more attention to the stability analysis for future construction guidance. Different backgrounds may also have different views on classification. Schultz and Cleaves (1955) have a very good explanation as follows:

"As a rule, the geologist confines his studies to mass movements

that have already taken place, and analysis of the stability of existing slopes usually does not enter into his consideration. The civil engineer is less interested in past slides than in future possibilities, and analysis of slope stability forms an important part of soil mechanics."

However, one who needs to develop an appropriate landslide classification for his purpose and region should not overlook the existing outstanding classifications of the others.

Sharpe (1938) has made a brief review of landslide classifications before 1938. He introduced the classification works of A. Baltzer, Albert Heim, Albrecht Penck, David Molitor, Gustav Braun, Ernest Howe, Josef Stiny, Roberto Almagia, Walther Penck, Karl Terzaghi and many others. Also, he listed a bibliography of 275 references for general classification and for different types of landslide.

Since 1938 many additional classification criteria have been devel-

oped. Consequently it is impossible for the writer to cite all the related literature in such a limited space. However, he wishes to review what seems important to him and at the same time to present some information from different countries. The list is as at the middle of this page.

### I. Heim's Classification

Probably Professor Heim was one of the first who made a special study of landslide phenomena in the Alps. According to Howe (1909), Heim's classification is as the bottom of this page.

Howe admitted that the translation of the classification was not perfect and it was unfortunate that the two English words "landslip" and "landslide" should be used, since both slip and slide imply smooth and easy motion. He also pointed out that "there is no term in common use to describe such movement as 'Felsstürze' and to bring out the distinction between them and 'Felschlipfe'."

Name	Nation	Year	Basis of Classification
1. A. Heim	Switzerland	1882	Material and movement
2. D. Molitor	United States	1894	Causes
3. G. E. Ladd	United States	1935	Structure and material
4. R. G. Hennes	United States	1936	Mechanics
5. C. F. S. Sharpe	United States	1938	Movement, material and moisture
6. D. J. Varnes*	United States	1958	Movement and material
7. I. V. Popov	U.S.S. R.	1946	Age and region
8. T. K. Wakeyuzo	Japan	1912	Material and movement
9. H. Koide	Japan	1955	Causes and material

\*In Highway Research Board Special Report 29 "Landslides and Engineering Practice." 1958

Bergstürze (Landslides)	{	Schuttbewegungen (movement involving detritus)	{	I. Schuttrutschungen (soil slips)	
				II. Schuttstürze (earth slides or falls of greater than I.)	
		Felsbewegungen (movement involving solid rock)	{	III. Felsschlipfe (rock slips)	
				IV. Felsstürze (rock falls)	
		V. Gemischte and zusammengesetzte (compound slides with respect to character of movement and of materials)			
		VI. Besondere (unclassified and special cases)			

According to Howe, Heim himself commented on the use of the word "Bergsturz," stating that it should be understood to mean the "fall of more or less material from the side or face of a mountain" and not the "fall of a mountain." Heim also restricted the term "Felsschlipfe" to cases where stratified rocks have a dip in their direction of the slope while the term "Felsstürz" is applied to the movement of rock masses independent of their original attitude or individual character.

It is apparent, in Heim's classification, that I and II differ in degree, III and IV differ in type of movement whereas V is a combination of the previous types. Type VI includes all other types.

Heim's classification is rather simple and there is some confusion in the last two types (V and VI). However, he had tremendous influences on the early popular classification by Howe in the United States, and also on landslide classification in Japan.

## II. Molitor's Classification

David Molitor was the first one in the United States presenting a comprehensive classification of landslides primarily based on the causes of movement. He classified landslides into four groups as follows:

- (a) Those occurring where the slope is too steep to maintain equilibrium of the mass.
- (b) Those caused by inclination of the natural strata, combined with lubricating action of water. In this and in the previous case we find a clearly defined sliding surface.
- (c) Slides caused by the action of water alone. Here the material is softened to such a degree

that it becomes fluid.

- (d) Where the underground is not capable of supporting the weight of the overlying fill material.

Molitor explains that slides in group "a" are usually caused by cuts or fills, or by stream washing of the foot of a slope. For group "b," a sidehill cut or rainfall will assist in producing motion. In group "c," springs, strata carrying water, and the presence of water in a crack usually gives a clue to the cause. The last group "caused by a giving way of the underground, owing to the insufficiency of its supporting power."

Molitor's work based on major causes is worth our attention.

## III. Classifications by Ladd and Hennes

Before Sharpe's classification, two outstanding papers dealing with landslides and their classifications by Ladd (1935) and Hennes (1936a) are still extensively quoted today.

Ladd in his article entitled "Landslides, Subsidence and Rock-fall: as Problems for the Railroad Engineer," has divided landslides into five main classes: (1) flows, (2) slope readjustments, (3) undermined strata collapse, (4) structural slides, and (5) clay ejection from ancient clay-filled caves opened by cuts. Under these headings he further grouped seventeen types. He discussed subsidence and rock-falls separately because they did not fit in his restricted definition of landslide. The last part of Ladd's article deals with methods of prevention and control which is particularly valuable.

Hennes (1936a) considered mechanics rather than geology in classifying landslides into the following categories:

True slide:

1. Rupture in essentially ho-

ogeneous materials

2. Rupture in essentially heterogeneous materials
  - a. Due to uplift
  - b. Due to trapped water
  - c. Along joints, bedding planes and other zones of weakness

Plastic flow:

1. Homogeneous clay
2. Sand
3. Creep

Collapse:

1. Cohesive subsoil
2. Pervious subsoil

He claims that the manner of failure serves as a convenient basis for the classification of landslides. His explanation of "Rupture," "Flow" and "Collapse" is as follows:

**Rupture:** The displacement of a body of soil moving essentially as a unit along a fairly well defined surface of cleavage.

**Flow:** If the shear is not restricted to such a surface but spreads generally throughout some zone of disturbance in the soil in the form of a differential displacement, it has the nature of a flow.

**Collapse:** When the failure occurs less in shear than in flexure, through the withdrawal of underlying support, the result is collapse.

Hennes (1936 b) believes, "It is sufficient for engineering purposes to group slides under the three headings of rupture, flow and collapse in discussing appropriate methods of control." It should be mentioned that Hennes' classification into three major types may throw some light on Varnes' classification

in the Highway Research Board's report in a later year.

#### IV. Sharpe's Classification

The most famous classification which has been used to a great extent is C. F. S. Sharpe's. His classification (1938) is based on three factors: (1) the kind and rate of movement, (2) the kind of material involved, and (3) the water or ice content of the material.

Sharpe's attempt is to form a "continuous series" of mass movement phenomena that will reflect "grading from mass movement of dry earth or rock into mass-transport by fluvial and glacial processes." He put landslides and other processes of denudation primarily in a descending order of water content as follows:

Stream-flow: Much water, small load, low angle

Slopewash

Sheetflood

Mudflow

Earthflow

Debris-avalanche

Landslide: Little water, large load, moderate to high angle

Sharpe also grouped mass-movement into four major types:

Slow flowage: Rock-creep, talus-creep, soil creep, rock-glacier creep and solifluction.

Rapid flowage: Earthflow, mudflow, and debris-avalanche.

Sliding: Slump, debris-slide, debris-fall, rockslide, rockfall.

Subsidence: Sinking of ground over mines, caves, etc.

Most of the above-listed types have been explained in a previous section "Types of Landslides." Figure 2-4 is Sharpe's landslide classification chart.

Sharpe's systematic classification, based on his keen observation of natural

	MOVEMENT		ICE	EARTH or ROCK	WATER			
	KIND	RATE						
			CHIEFLY ICE	EARTH OR ROCK PLUS ICE	EARTH OR ROCK, DRY OR WITH MINOR AMTS OF ICE OR WATER	EARTH OR ROCK PLUS WATER	CHIEFLY WATER	
WITH FREE SIDE	FLOW	USUALLY IMPERCEPTIBLE SLOW TO RAPID	GLACIAL TRANSPORTATION	ROCK CREEP			FLUVIAL TRANSPORTATION	
				TALUS CREEP				
				SOLIFLUCTION	SOIL CREEP	SOLIFLUCTION		
						EARTH FLOW		
						MUD FLOW SEMI ARID, ALPINE, VOLCANIC		
				DEBRIS AVALANCHE				
	SLIP (LANDSLIDE)	PERCEPTIBLE RAPID SLOW TO RAPID		GLACIAL TRANSPORTATION		SLUMP		
						DEBRIS SLIDE		
						DEBRIS FALL		
						ROCKSLIDE		
			ROCKFALL					
NO FREE SIDE	FAST OR SLOW							
				SUBSIDENCE				

Figure 2-4. Classification of Landslides and Related Phenomena (After C.F.S. Sharpe 1938).

TYPE OF MOVEMENT	TYPE OF MATERIAL			
	BEDROCK		SOILS	
<u>FALLS</u>	<u>ROCKFALL</u>		<u>SOILFALL</u>	
<u>FEW UNITS SLIDES</u>	ROTATIONAL <u>SLUMP</u>	PLANAR <u>BLOCK GLIDE</u>	PLANAR <u>BLOCK GLIDE</u>	ROTATIONAL <u>BLOCK SLUMP</u>
		<u>ROCKSLIDE</u>	<u>DEBRIS SLIDE</u>	<u>FAILURE BY LATERAL SPREADING</u>
<u>MANY UNITS FLOWS</u>	ALL UNCONSOLIDATED			
	ROCK FRAGMENTS <u>ROCK FRAGMENT FLOW</u>	SAND OR SILT <u>SAND RUN</u>	MIXED <u>LOESS FLOW</u>	MOSTLY PLASTIC
			<u>RAPID EARTHFLOW</u>	<u>DEBRIS AVALANCHE</u>
<u>WET</u>		<u>SAND OR SILT FLOW</u>	<u>DEBRIS FLOW</u>	<u>MUDFLOW</u>
<u>COMPLEX</u>	COMBINATIONS OF MATERIALS OR TYPE OF MOVEMENT			

Figure 2-5. Classification of Landslides, Abbreviated Version (After Highway Research Board Landslide Committee, Special Report 29, 1958).

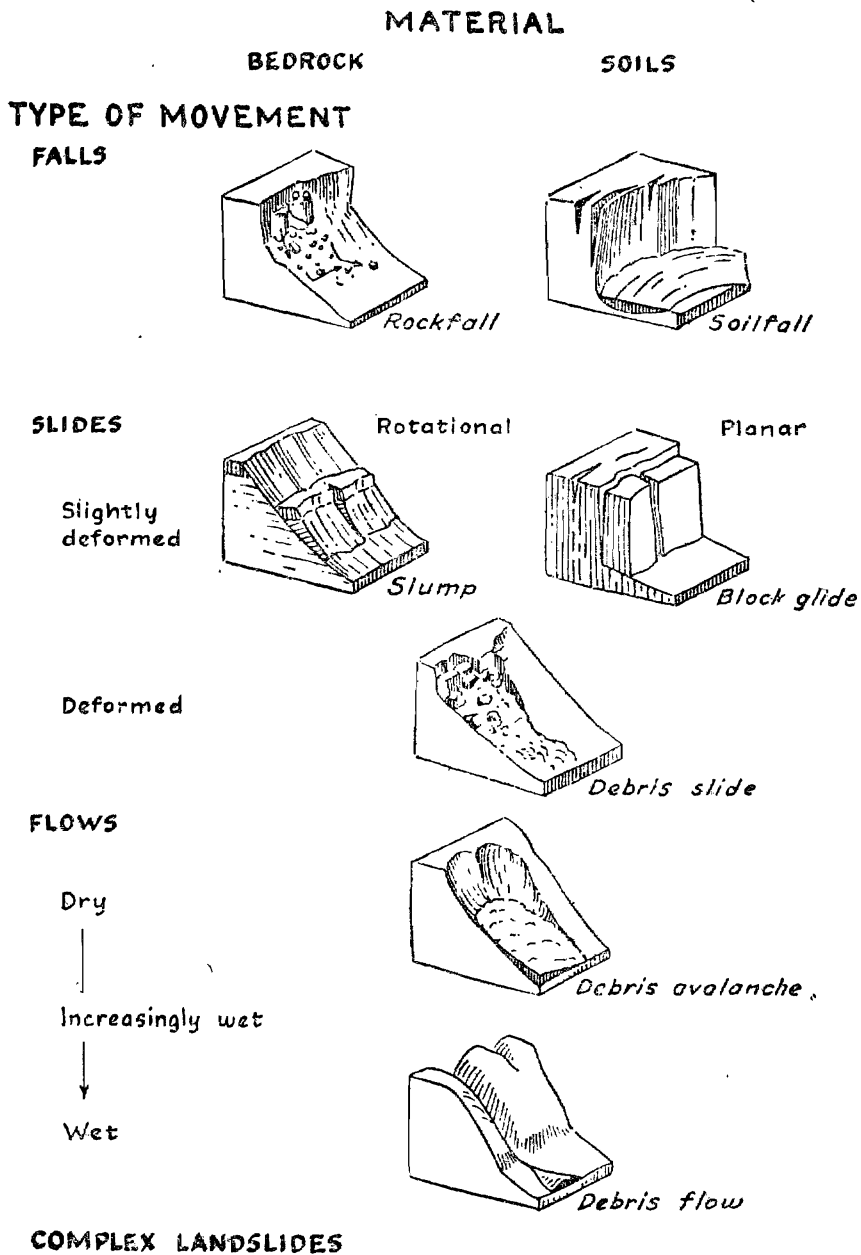


Figure 2-6. Simplified Diagram of Types of Slides and Rockfalls (After Highway Research Board Landslide Committee, Special Report 29, 1958 and Leopold et al. 1964).

phenomena, has been accepted widely ever since. However, there are some comments about his work which we should not neglect to mention. Thornbury (1954) commented on Sharpe's mass movement series and said:

"The difficulty encountered in drawing sharp lines between these different types of transport merely emphasizes that in setting up definitions we often suggest fine distinction which do not exist in nature."

After extensive study of landslides in the United States using both aerial photos and field investigations and employing primarily Sharpe's classification, Liang (1952) pointed out that usually landslides are a combination of two or more types.

Parizek and Woodruff (1957) in their article, "A Clarification of the Definition and Classification of Soil Creep", have commented on Sharpe's loose definition on creep. They subsequently made a drastic change in the definition, and revised the subtypes involved in flowage.

#### V. Varnes' Classification

A later classification of landslides worth special mentioning is that of Varnes' of the Highway Research Board (HRB) of the United States. Under HRB there is a committee of landslide investigation. In 1958 a special report was published, "Landslides and Engineering Practice," dealing with many aspects of the landslide problem. Varnes contributed one chapter entitled "Landslide Types and Processes" to this report.

In Varnes' classification, no consideration has been given to subsidence, creep and solifluction. Eckel, the editor of the report, also commented that landslide phenomena in tropic and arctic climates were "almost entirely neglected" in this report.

The whole scheme of classification

is based upon types of movement and material. As indicated by Varnes, "Two main variables are considered: (a) the type of material involved, which usually is apparent on inspection or preliminary boring, and (b) the types of movement, which usually may be determined by a short period of observation or by the shape of the slide and arrangement of debris."

Types of movement are divided into four groups: falls, slides, flows and complex. Under the first three groups eighteen types are listed and illustrated, most of which have been discussed in the previous section. The classification chart is shown in Figure 2-5 (Note that the various types of landslides are underlined). A simplified diagram of the major types is shown in Figure 2-6.

Varnes has explained his original intention: (1) to classify these movements according to factors which have some bearing on prevention or control, and (2) to make a deliberate effort to set the classification up according to features that may be observed at once or with a minimum of investigation, and without reference to the causes of the slides.

However, as the writer mentioned in the previous section, to distinguish the eighteen proper types of classification still needs considerable time and precision. To neglect the "causes" totally in this classification, on the other hand, is not always appropriate and desirable from the treatment standpoint.

#### VI. Popov's Classification

According to Krynine (1960) the current methodology of landslide investigation in Soviet Russia is emphasizing two factors, time and region. He mentioned that Savarensky was the first in Russia to introduce into the slide classification the time of manifestation

of the slide and its state (stage). The classification was then modified by Popov. Popov(1946) himself believed: "Landslides are historical-geological processes, dependent on the history of development of a given region, and having a history of their own." He further pointed out that landslides were in the first place subdivided according to their age into: (a) landslides corresponding to the present position of the base-level of erosion and level of abrasion, and (b) landslides which started in the geological past, when the positions of these levels were different. In the second place, landslides are distinguished according to the phases of their development. Figure 2-7 is Popov's modified slide classification. Recently, Popov (1963) emphasized that climate patterns also affect the distribution of landslide activity. He stated:

"Certain types of mass-wasting phenomena may be referred to climate zones of definite character: solifluction to snow-covered and polar regions (especially zones with prolonged permafrost), slide rock and

talus to arid and semiarid regions with precipitation in brief violent showers and to climate zones of the high mountains where physical weathering is widespread, rock glaciers to humid temperate and humid tropical zones, and so forth."

In addition, he suggested that an analysis of the relationship between regional tectonics and the development of landslides at the present time is very desirable.

Although Popov's classification is only partial his ideas about age of landslides and regional approach are quite valuable.

Coincidentally, in the United States, Baker and Chieruzzi (1959) have discussed in great detail the regional concept of landslide occurrence. Liang (1952) has also recognized the importance of finding the cause of old slides. Jones et al. (1961) has classified 300 more landslides along the Columbia River Valley, Northeastern Washington, into three major type groups. One of these was age: recent or ancient.

Age	Phases	Characteristic	
		of age	of phase
Recent	Moving	With recent baselevel of erosion and level of abrasion	Process of establishment of equilibrium continues
	Suspended		Operation of cause temporarily balanced by agent of security
	Arrested		Cause temporarily eliminated
	Completed		Operation of cause exhausted
Ancient	Open	With a different position of the former	Nothing but soil and eluvium on the surface
	Buried		Covered by later deposits

Figure 2-7. A scheme of Classification of Landslides According to Their Age and Phases (After I.V. Popov).

VII. *Classification by Wakeymizu and Koide*

From Wakeymizu to Koide one can see the general trends of landslide classification in Japan. Probably Wakeymizu was the first one who made a landslide classification which became a widely accepted classic in Japan. His classification, according to Nakamura (1955), is as the bottom of this page.

The difference between "landslide proper" and "landslip," is explained by Nakamura. The former is broken into pieces after displacement whereas the latter is not. The causes of "landslide proper" are heavy storms and earthquakes while the causes of "landslip" are the presence of subsurface water or of a weak layer.

Apparently Wakeymizu's classification resembles somewhat the work of Heim. Yet the important idea is that "landslide" and "landcreep" are separated into two groups. This idea, after a half of a century, is still prevalent among scientists in Japan.

Many other classifications have been developed in Japan, however, the recent classification by Koide (1955) receives more attention. His classification for landslides and landcreeps is summarized as follows:

Landslide:

1. Caused by heavy storm, earth-

Landslide	{	A. Landslide proper	(1) Rockfall, Felssturz
Landslip		B. Landslip	(2) Earthfall, Erdsturz
Bergsturz		(3) Landslide in large scale	(1) Rockslip, Felschlipf
			(2) Earthslip, Erdschlipf

Landcreep	{	A. Slow landcreep*
Erdkriechen		B. Landcreep proper

quake and groundwater.

2. Caused by gully and stream erosion.

Landcreep:

1. Detritus creep
2. Bedrock creep:
  - a. Intermittent
  - b. Continuous
3. Clay creep

It is apparent that Koide classified landslides based on causes, and landcreep on material. His lengthy years of active participation in the field investigations in Japan resulted in his simple classification. Murano (1962) explained Koide's classification in his detailed report on sediment production of mountain watersheds in Japan. Noguchi (1963) of the Tokyo University also adapted Koide's classification with minor modifications in his book, "Forest Influences." He pointed out that from the damage prevention and control standpoint we have to separate landslide and landcreep although they are hard to distinguish. He also explained the following:

"it is academically valuable to classify landslides based on geologic types. However, this kind of classification has less value to the work of prevention and control. On the other hand, the classification based on causes such as direct action of water etc., will help the

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\*This term is the writer's translation from Mr. Nakamura's interpretation. It moves more slowly than the "Landcreep proper" due to development of a weak layer beneath.

programming of control projects. The latter classification, therefore, may be called 'technological classification' which provides the basic information for sediment control work."

### **Possible Treatment and Correction**

Most people consider that treatment and correction of failures on artificial slopes, such as on road banks, dams and levees, are necessary. For landslides on natural slopes, however, their philosophy is often different. They may think of the latter as an "act of God," or may feel that it is geologic erosion which man can do little about. This is true, in the sense of geological time, no slope can be regarded as being permanently stabilized. But, as mentioned before, man can feasibly stabilize a slope for a desired period of time if such action is justified.

No two slides are exactly the same. As Forbes (1947) has pointed out, "Each slide requires the determination of the conditions unique to the area before plans are formulated for correction." "But," he further stated, "methods successful in one case may generally be adapted successfully to meet the conditions encountered in other cases."

There are undoubtedly a number of causal factors involved in any landslide as mentioned previously. However, there must be a dominant one. Baker (1953) realizes "of great importance is the fact that by eliminating or by modifying the effect of any one of the causes the stability will increase." Holmsen (1953) also indicates that any efforts to counteract possible landslips imply attempts to prevent the initial one.

For convenience sake, landslides are to be arbitrarily divided into two groups, namely: those occurring on artificial slopes and those on natural slopes. It does not necessarily mean that the treat-

ments and corrections for these two kinds are entirely different. Some work certainly can be applied to both types. But, in general, artificial slope receives more intense treatment than natural slopes.

#### *I. For Artificial Slopes*

The term "artificial slope" here implies not only the man-made or constructed slope but also the slope which has been partly excavated or deposited by human activities. It includes, therefore, road slope, levee, dam, reservoir bank and mining spoil bank.

The artificial slope usually needs treatment and correction when it fails. Preventive work is also more important on such slopes than it is on natural slopes (on which prevention measures may frequently be impossible). Among this group, road or highway slopes may deserve much more attention than others due to their overwhelming quantities and extensive distributions.

The Highway Research Board (HRB) and the Bureau of Public Roads of the United States have been doing numerous studies, investigations and actual work in correcting, controlling and preventing landslides. Their main purpose is to stabilize road slopes, however, many principles involved can be applied to other artificial slopes or natural slopes as well. Many other agencies in the states of California, West Virginia and Ohio etc., are also actively engaged in the slope stabilization task.

In this section only the fundamental principles involved in the treatments and corrections are to be reviewed. Because it is futile to discuss specific details without knowing the site in question. Most information in this section is from the above mentioned sources.

The work to be discussed is as follows:

1. Avoidance: Relocation, bridging

and other.

2. Excavation: Removal, flattening and benching.
3. Drainage: Surface and subsurface drainage.
4. Supporters: Retaining walls, cribs, piling, and anchoring.
5. Other methods: Hardening, blasting, and vegetating.

1. Avoidance:

Avoidance is primarily a prevention measure and belongs to the stage of planning. Sometimes it is wise and economic to avoid building a highway or structure in a potential sliding area or area of instability. Root (1958, in HRB report) pointed out, "although it is not often feasible to avoid a potential slide by changing the location of a proposed highway or structure, the possibility should not be overlooked." He also mentioned that a revision in the grade line of a proposed highway may be equally effective in preventing slide movement and it does not necessarily require a change in alignment or location of a highway.

Besides relocation, bridging is another way of avoidance in highway construction. Sidehill viaducts are commonly used for spanning the moving mass. Bridges are normally high in cost. Baker and Marshall (1958, in HRB report) advised that bridge lengths greater than 100 to 300 feet were economically doubtful if the methods compared with other possibilities. They also suggested being careful not to place the abutments on material of instability.

It is also a good practice to avoid dumping mining waste or excavation material at areas of instability.

2. Excavation:

Excavation methods are primarily used to increase the stability of the

sliding area by reducing the moving forces. They can be employed on both artificial and natural slopes.

Generally speaking, this method is cheaper than corrective construction if stability can thus be obtained. The principal methods are: (a) removal of sliding or all the unstable material, (b) flattening the slopes, and (c) benching.

Removal of the sliding mass sometimes is a remedial measure. However, as indicated by Cleaves (1961), removal of debris at the toe may aggravate an already serious condition. In that case, alternatives or additional measures should be considered.

In California, Root (1953) reported that by constructing a strut fill at the toe of the slide and removing a small amount of material near the head, the factor of safety would be increased from 0.8 to about 2. He also mentioned that at rock slide areas correction usually consists of flattening out cut slopes, often in conjunction with unloading of slide and construction of benches.

Finzi et al. of Italy (1961) also reported that on the banks of the Monguelfo Reservoir where slope protection by structure was not appropriate due to lack of firm foundation, the method of flattening bank slope by the addition of suitable material was successfully employed.

Benching provides stability of slope by dividing the long slope into segments. Under proper design the runoff can be diverted to a safe outlet without causing erosion. Cleaves (1961) states, "Benching is particularly effective where massive beds of hard rock overlay thinly bedded, easily weathered materials."

3. Drainage:

Drainage may be important in almost any cases of landslides. However, under

certain conditions we should not overlook the other possible treatments. Hennes (1936a) offers a particular caution, "any attempt at gravity drainage of a clay which has attained equilibrium under the weight of overlaying soil is doomed to failure, because the resistance to ground flows through clay is so high."

Surface drainage is employed to deconcentrate runoff, to conduct water to a safe outlet or to decrease infiltration of water to the sliding mass. Open ditches are commonly used above the crown of the slide for diverting or intercepting purposes. As stated by Baker and Marshall (1958, in HRB report), "Unless it is sloped so as to provide fast drainage or unless its base is sealed with impermeable material, it can easily become a device for feeding water into the slide rather than as a remover of water." Other treatments like reshaping, sealing of cracks, slope treatment by sodding, oiling and rip-rapping, etc., are usually employed together to improve the surface runoff conditions of the sliding mass.

Subsurface drainage is used where groundwater exists. It includes horizontal drains, drainage trenches, tunnels, vertical drains and continuous siphons, most of which are expensive and need sound justification.

The object of horizontal drains is to lower the water table in the slide mass. Enough drilling is needed to determine where water is present and whether it can be removed from the ground. Metal pipes of a few inches in diameter are placed into a predrilled hole at a gentle gradient. Root (1958, in HRB report) indicated that the slope of the pipe may range from 5 to 25 percent and the length may be as great as 200 to 300 feet or more. Fukuoka (1961) of Japan reported that the most effective method to control a large creep in

Ishikawa Prefecture was found to be horizontal boreholes long enough to release the underground water from below the planes of rupture.

Trenches and tunnels can be used to a limited extent. Where groundwater can be intercepted at depths of less than 10 to 15 feet, drainage trenches can be employed. Drain pipe should be based on unyielding material. Tunnels are used for large and severe sliding areas. The size is usually about four by six feet in cross-section and at some places an ingenious hot-air furnace is used for drying out the soil.

Vertical drains are used in conjunction with horizontal drains to provide a drainage path between strata of water bearing materials which are separated by impervious strata as indicated by Root. They may also be installed under embankments to remove water in weak compressive foundation soils. Continuous siphons have been used successfully in the state of Washington. Both of these treatments, however, are infrequently employed.

#### 4. Supporters:

Retaining walls, cribs and other supporting or restraining structures are commonly used as corrective methods as well as for prevention treatments. The toe of a sliding mass usually moves upward. By adding weight in the form of a toe support, as indicated by Root (1958, in HRB report), the resistance against sliding is increased. However, these supporters do have their limitations where the driving force and moving mass are great. Baker and Marshall (1958, in HRB report) mentioned that the following information will be needed to determine the size of these structures: (1) areal limits, (2) depth of soil overburden or rupture surface, (3) relative stability of

the moving mass and type of movement, (4) foundation conditions, (5) moisture condition in the moving mass, and (6) value and relative location of structure involved.

Piling is used to increase the resistance of slumps by enlarging their slipping planes. According to Liang (1952), piling is often feasible in shallow slides and where a competent bed exists below. Krynine (1931), after explaining theoretically the piling effect, stated: "Therefore, in order to increase the sliding resistance of a slope it seems adequate to bore deep holes in the slope (not at its foot, but higher) and either fill the holes with concrete or introduce ready-made concrete or wooden piles in the hole."

Rockslides can be stabilized by rock bolting and dowelling. As suggested by Cleaves (1961), wire mesh can be draped over the slope face to protect from bounding rock.

#### 5. Other Methods:

Soil material can be successfully hardened by injections of cement or chemicals, or by the electro-osmosis method. Hardening will increase shear strength of the moving mass, particularly along the surface of rupture. According to Root, cement injections have been used successfully in coarse sands and gravels, but are generally considered less effective with finer grained soils. Sodium silicate, in combination with other chemicals, is used to form a silica-gel in the interstices of the soil. Electro-osmosis methods are to be employed to reduce soil moisture and to lower groundwater level. Casagrande et al. (1961) reported a successful case of applying this method to stabilizing high slopes or loose saturated silt in Marathon, Canada. After three months of applica-

tion, he found that the average water content had decreased by about four percent and the groundwater level in the silt stratum was lowered 33 to 45 feet.

Blasting is sometimes applied to produce better drainage beneath the surface of rupture and where a hard layer is underlain by a pervious formation. It may also be used to break up a critical surface of rupture thus increasing the shearing resistance. (Cleaves 1961, Baker and Marshall 1958, in HRB report). In applying this method careful judgment should be made as to whether the desirable ends can be achieved or whether the method may cause more harm than good.

On artificial slopes sodding and tree planting are often employed to protect them from erosion. To select species which offer quick growth and better cover and which require a minimum of maintenance is essential.

## II. For Natural Slopes

Due to location, landslides in wildland or forested watersheds receive less attention from the public. These landslides are not usually subject to treatment unless they endanger reservoirs, buildings, roads or other important installations below. Check dams, revetments, benchings, diversions, and revegetation may be applied to provide direct correction or indirect protection of the sliding area.

### 1. Check Dams and Revetments:

Check dam of various kinds have been used as the indirect treatment of landslides in Japan as well in Taiwan. Fukuoka (1961) of Japan indicated, "It was found that the best method of stopping debris flow was to build dams at the foot of the valley."

Generally speaking, a check dam has many functions: (1) to arrest the sediment or debris from the slides so as to reduce damages below, (2) to protect

the toe of the slide when the dam is filled up, (3) to prevent down cutting of the stream bed, and thus reducing the hazard of sliding due to oversteepening, and (4) to check the flow velocity, to raise and widen the channel and to confine the channel alignment so as to decrease bank cutting.

Many people think that the function of a check dam stops as soon as it is filled up. However, Yano (1962) of Japan pointed out:

"It may be wrongly thought the function of sabo dam\* ends upon the completion of sand storing, but it actually functions as a mud controlling device even after the sand storing is over."

Nakamura (1955) has mentioned that check dams built on old deposits of creeping or sliding material have less effect and are bound to fail. Fukuoka (1953) had also reported check dam failure of this kind.

Revetment is to be used mostly along the curvature of a stream bank or to protect the toe of the slopes in question. It should be built high enough to provide protection during flood time.

## 2. Benching and Diversions:

Benching and diversion ditching are usually employed to improve surface drainage of the slope. Benching is particularly good to stabilize slopes and

is employed extensively in Japan and Taiwan for slope stabilization. In humid areas, benches should be built reverse sloped. According to Landon (1963) "Benches should be finished with a slope of at least ten centimeters toward the hill." By constructing the bench higher at the outside brink and sloping toward the toe of the upper one, the excess water can be collected at the cut area without overflowing the loose bank causing damage. A protected waterway is always needed to receive excess runoff from the benches and to divert it to a safe place. Chou (1960) indicated that narrow benches and revegetation are usually used together for stabilizing sliding area.

The construction of a diversion ditch is somewhat like a single bench except that it is usually located above the unstable area.

## 3. Revegetation:

Grass reseeding and reforestation are usually employed on the natural sliding slopes. The purpose of revegetation is primarily to prevent surface erosion which may enlarge to gullies and promote instability of the slope. Seeding or sodding can also improve surface drainage conditions (Baker and Marshall 1958). In Japan, the term "sabo reforestation" is a proper name for reforestation on severely eroded or landsliding area. This kind of reforestation usually demands mechanical stabilization work as a prerequisite.

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\*Check dam or soil saving dam in Japanese language

## DESCRIPTION OF THE STUDIED AREAS

Three mountain watersheds in Taiwan have been studied: Shihmen, Tsengwen and Wanta. Their locations and general features are given in Figure 3-1 and Table 3-1.

### Shihmen Watershed

#### I. General Description

The Shihmen watershed with a total area of 763.4 square kilometers is one of the important watersheds in northern Taiwan. It is situated at the headwater of Takokan Creek and is the catchment area of the newly completed Shihmen Reservoir. This installation not only provides irrigation water to 58,000 ha. of land and generates 90,000 kw. of electricity, but also functions as a flood control facility for the area of Taipei, the capital of the Republic of China. The watershed partially covers Taoyuan County, Hsinchu and Yilan Counties. Ninety-seven percent of the area is classified as national and public lands and three percent is in private ownership.

#### II. Physical Description

##### 1. Topographic Characteristics:

The kidney-shaped watershed has an average width of 17 kilometers and a length of 45 kilometers. The elevation of Shihmen Dam, in the lowest and northwest corner of the watershed, is 250 m. above sea level whereas the highest peak, Pin-tien, is 3,529 m. at the south tip of the basin. There are, in all, five peaks over 2,500 m. elevation. The watershed has an average elevation of 1,765 m. The whole watershed is oriented north-westerly. Except for the tablelands close to the reservoir, most slopes are steep, being between 25° and 45°.

##### 2. Drainage Features:

The drainage pattern for the entire watershed is dendritic. The Takokan Creek originates at an elevation of 3,100 m. near the south end of the watershed and flows north and then west to the Shihmen Dam. The total length of the main stream is 90.5 kilometers and the average fall is 33 m. per kilometer.

##### 3. Shihmen Reservoir:

Shihmen Reservoir is approximately 16.5 km. long and 0.5 km. wide with an eastwest orientation. It occupies a surface area of 8 square kilometers at full. Its total storage capacity is 316,000,000 m.<sup>3</sup> and the dead storage is provided for 65,000,000 m.<sup>3</sup>. The dam was completed in 1963 at a total cost of about one hundred million U. S. dollars.

##### 4. Geology:

This watershed is composed mostly of rock formations of the Tertiary Period. The general regions are as follows (see Figure 3-2):

- (1) The southeast upstream region: This region is mainly underlain by Eocene formations. It lies in the north end of the Central Range. Quartzites and slates are the principal bedrocks.
- (2) The main region: This region is underlain by Oligocene formations and constitutes the major part of the watershed from the headwater of the watershed down to the Chiao-pan-shan villgae, near the west end of the reservoir. The rock types are slightly metamorphic shales, slates, and hard sandstones. Well developed joints are

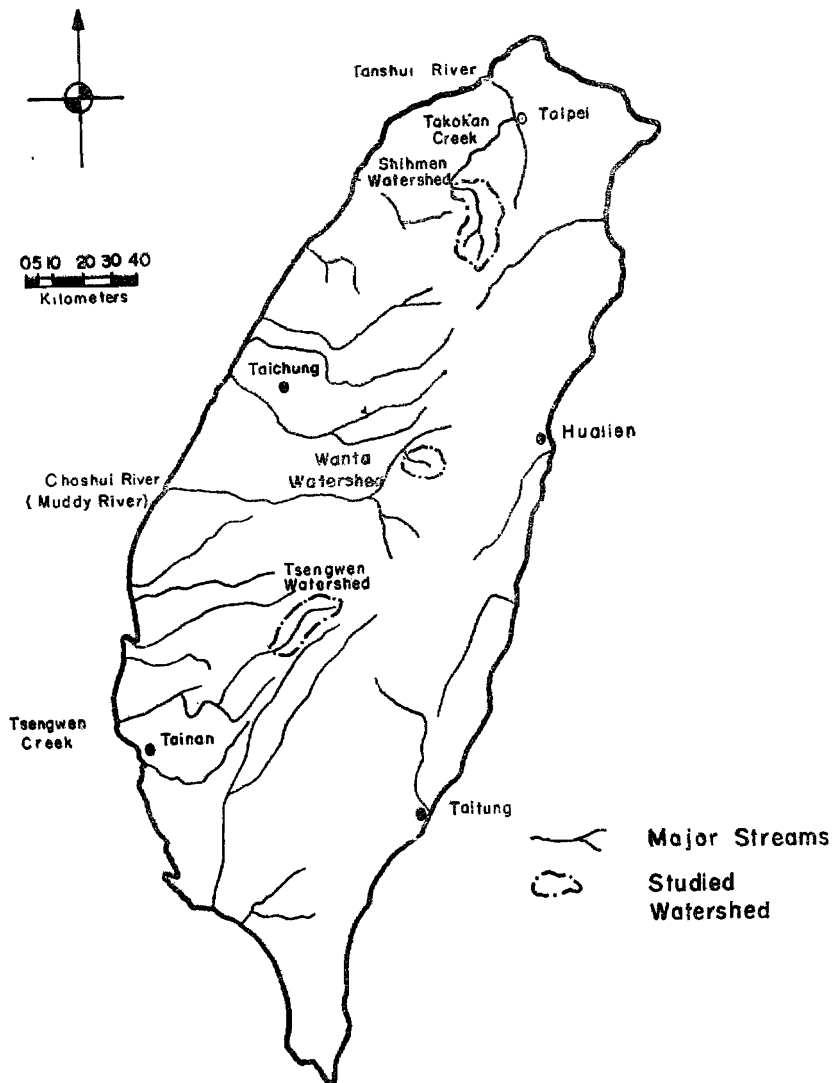


Figure 3-1. Location Map of the Studied Watersheds

Table 3-1. General Characteristics of the Studied Watersheds

Watershed	Location	Area (Km <sup>2</sup> .)	Mean Elevation (m.)	Watershed Orientation	Percent of Forest cover (%)	Annual Rainfall (mm.)
Shihmen	Northern Taiwan	763.4	1,765	NW	91	2,500
Tsengwen	Southern Taiwan	475.8	963	SW	80	3,350
Wanta	Central Taiwan	222.4	2,000*	NW	68	2,380

\*Estimated from 1:250,000 topographic map

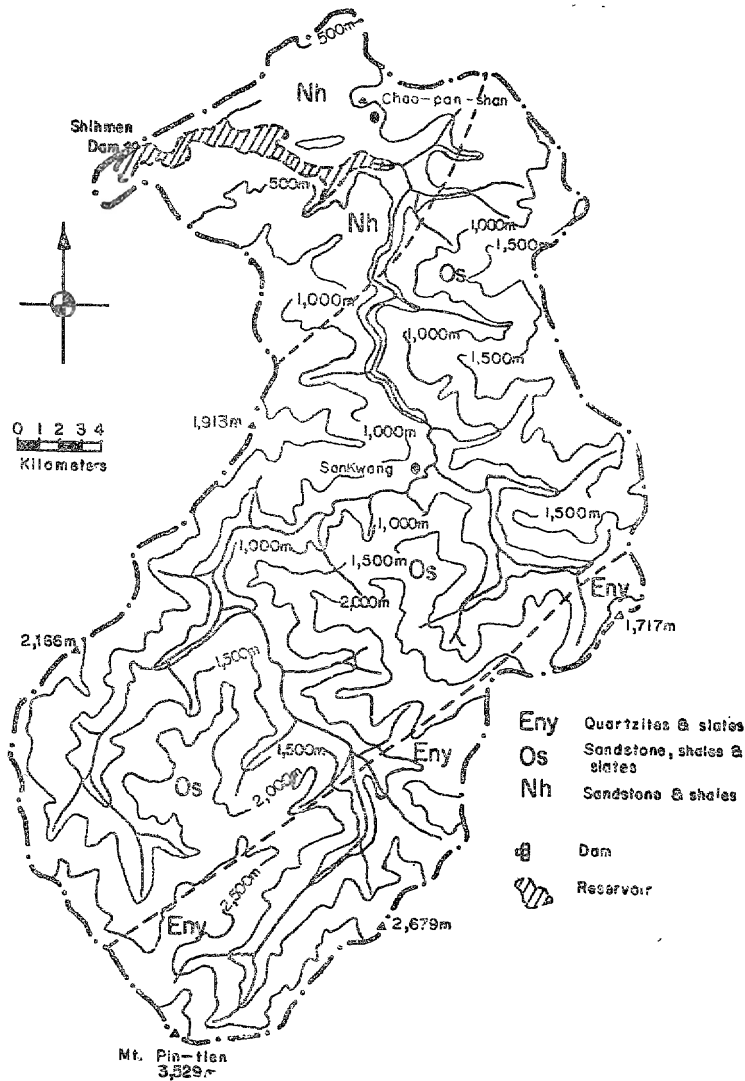


Figure 3-2. Topographic and Geologic Features of Shihmen Watershed

common in the hard sandstones and slates.

- (3) Reservoir region: From the Chiao-pan-shan village to the west, the majority of the land around the Shihmen Reservoir is underlain primarily by Miocene sandstones and shales. Pliocene soft and weak sandstones, finegrained sandstones, shales and conglomerates also outcrop in this region. Basalts and dolerites may outcrop locally.

#### 5. Soils:

There has been no detailed soil survey in the mountain areas of Taiwan. However, according to Chen and Leung (1962) of the Taiwan Agricultural Research Institute and the Shihmen Local Development Committee (1962) the soil groups of this watershed are as follows:

- (1) Mountain stony soils: They occupy most of the watershed. Formed primarily from hard sandstones and slates, the depths of the soils are approximately 30 cm. Colors vary from gray and

grayish-brown to pale brown and light yellowish brown. They have a high rock content, some as high as 70 percent. Due to their loose structure and to the steep slopes of the area erosion is quite severe. Fortunately most of these areas are under forest cover.

- (2) Reddish-yellow podzolic soils: They are derived from hard sandstones and shales. Occupying of the west half of the Shihmen Reservoir area, these soils have depths ranging from 50 to 90 cm. and have a gravelly medium texture. In color, they exhibit a pale brown surface, yellowish brown subsurface and brownish yellow bottom. They are strongly acid and less erosive than the stony soils.
- (3) Yellowish-brown lateritic soils: From Chiao-pan-shan down to the west, these soils are distributed at the lower half of the Reservoir area. Although variable in depth, some may be deeper than 90 cm. With a little finer than medium in texture they also contain rock fragments. They are weak in structure and pale yellow in color. Most of them are on the tablelands and are under cultivation.
- (4) Alluvial soils: Old alluvium soils are striped along the lower reaches of the stream. Soil depth ranges from 30 to 100 cm. They are pale yellowish-brown to yellowish-brown in color and their textures vary from medium to fine. Most of them have been developed as paddy fields.

### III. Climate

#### 1. Precipitation:

There are now eleven precipitation stations\* in this watershed, eight of which

have recording rain-gauges while the remaining three utilize the nonrecording type of equipment. Most of these stations were established in the early fifties and all of them now are operated by the Shihmen Reservoir Administration. Only a few stations such as Shihmen, Chiao-pan-shan and Sankwang have records of an appreciably longer time.

Precipitation in this watershed averages about 2,500 mm. (100 inches) annually. The average monthly rainfall and the number of rainy days at the three stations which have longer records are given in Table 3-2. Most of the rainfall occurs from May through September which is the typhoon season of the whole island.

Rainfall intensities on this watershed have broken world records. From September 9 to 11, 1963, Typhoon Gloria created world records of 15 hr., 18 hr. and 24 hr. at the Pai-shih station of this watershed. The 24-hour rainfall intensity was 1,248 mm. (50 inches). Figure 3-3 is the isohyetal map of the Typhoon Gloria in this watershed while Figure 3-4 is a comparison of point rainfalls between world records and records of two stations on this watershed.

#### 2. Temperature:

The monthly mean maximum and mean minimum temperatures of the three stations in this watershed are noted in Table 3-3. On the whole, the temperature in this watershed is rather mild, it seldom exceeds 32° C (90° F) or drops below 0° C (32° F).

#### 3. Humidity and Wind:

The relative humidity of this watershed is around 82 percent. It is quite steady all year round and only slightly lower from October through December.

Because there are mountain ridges to the north, and because the area is far from the sea coast, this watershed suffers very little from the winter monsoon. However, it

\*One station is outside of the watershed but very close to the Shihmen Dam.

Table 3-2. Average Rainfall and Number of Rainy Days of Shihmen Watershed

Month	Rainfall: mm.					
	Shihmen		Chiao-pan-shan		Sankwang	
	Rain-fall	Number of Days	Rain-fall	Number of Days	Rain-fall	Number of Days
Jan.	127.3	13.8	77.1	4.5	69.4	7.7
Feb.	203.6	15.4	145.5	10.9	79.4	8.4
Mar.	239.2	16.8	191.7	12.2	94.1	7.7
Apr.	242.7	15.6	203.7	12.3	134.5	10.6
May	261.8	16.2	305.9	14.9	191.0	11.0
June	469.0	17.1	383.1	16.6	290.0	15.7
July	450.6	17.1	385.0	16.2	290.4	14.7
Aug.	373.9	15.0	340.8	13.1	315.0	11.6
Sept.	247.8	11.7	284.8	10.0	273.2	11.1
Oct.	85.1	8.2	124.7	6.9	108.5	7.1
Nov.	78.4	9.0	66.8	6.8	92.5	6.8
Dec.	90.1	12.0	64.9	7.3	46.6	5.5
Ann.	2,869.5	167.9	2,574.0	131.7	1,934.6	117.9

Years of record: Shihmen 1926-1960

Chiao-pan-shan 1912-1960

Sankwang 1939-1960

Source: Taiwan Shihmen Local Development Committee 1962

Table 3-3. Average Temperatures of Shihmen Watershed

Unit: °C

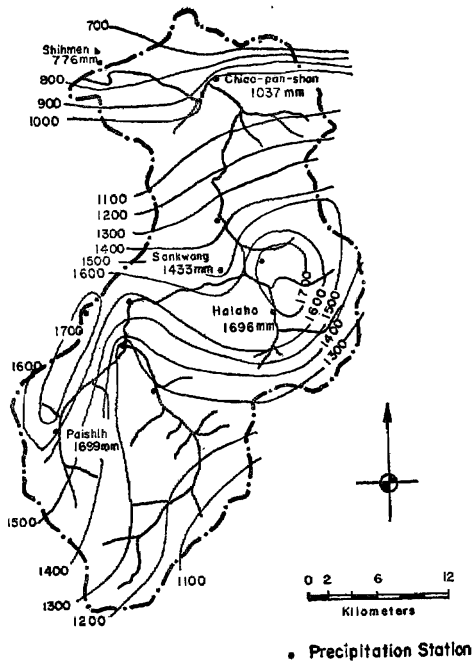
Month	Shihmen			Chiao-pan-shan			Sankwang		
	Mean	Mean Max.	Mean Min.	Mean	Mean Max.	Mean Min.	Mean	Mean Max.	Mean Min.
	Jan.	13.9	17.3	11.7	13.6	19.3	7.7	13.1	18.9
Feb.	14.3	17.4	11.4	14.2	20.2	7.0	14.6	19.8	9.9
Mar.	16.6	20.1	13.3	16.6	22.6	10.5	17.2	23.5	13.3
Apr.	19.6	23.6	16.2	19.4	24.7	13.3	19.9	26.0	15.0
May	23.3	28.4	19.3	22.5	26.5	18.4	22.9	28.9	18.7
June	25.5	30.8	21.4	24.9	28.2	20.9	24.3	30.6	19.9
July	26.6	32.5	22.4	25.7	29.1	22.5	25.1	31.5	20.4
Aug.	26.4	32.1	22.4	25.3	28.8	22.8	25.1	31.1	20.9
Sept.	25.2	30.1	21.2	24.6	28.3	20.5	24.0	29.8	19.9
Oct.	21.0	26.1	18.6	21.4	25.5	16.9	20.6	26.3	14.6
Nov.	18.9	22.8	15.6	18.6	23.2	13.8	18.2	24.0	12.5
Dec.	15.9	19.9	12.6	15.9	20.6	10.4	15.0	20.9	9.3
Ann.	20.6	25.1	17.2	20.3	24.8	15.4	20.0	25.9	15.2

Years of record: Shihmen 1950-1960

Chiao-pan-shan 1952-1960

Sankwang 1951-1960

Source: Taiwan Shihmen Local Development Committee 1962



● Precipitation Station

Figure 3-3. Isohyetal Map of Typhoon Gloria (Sept. 9-11, 1963) of Shihmen Watershed  
 Source: Shihmen Reservoir Administration

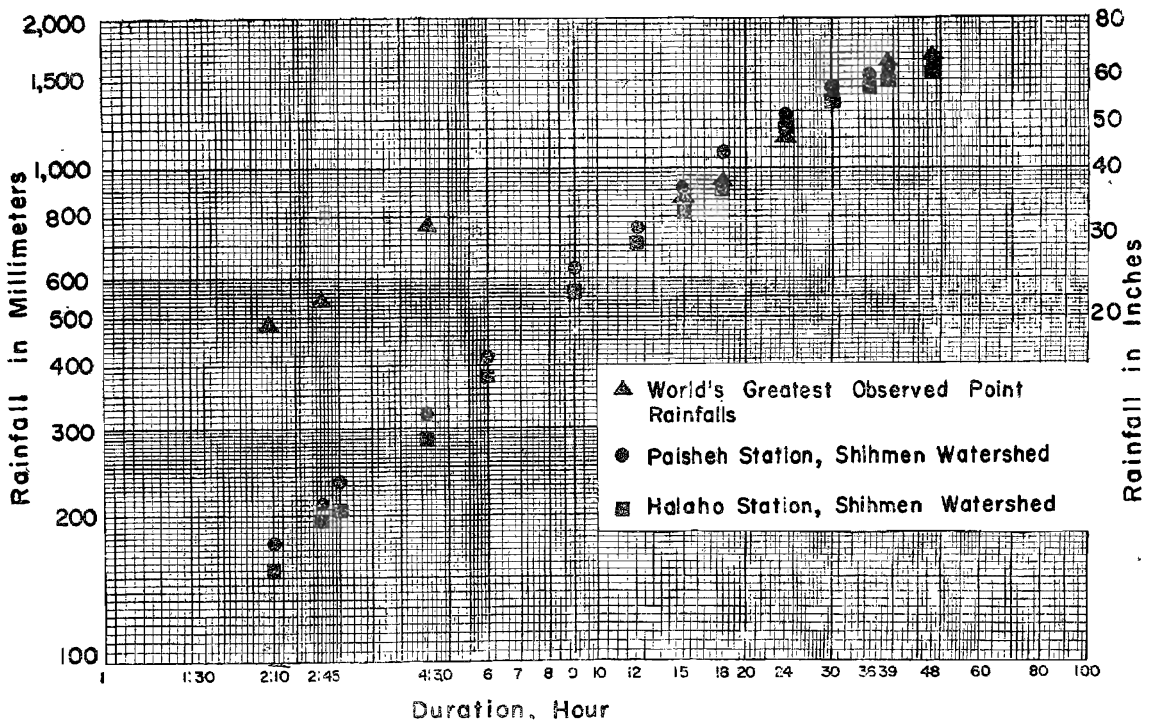


Figure 3-4. World's Greatest Observed Point Rainfalls vs. Recorded Point Rainfalls in Shihmen Watershed During Typhoon Gloria  
 Source: (1) Linsley et al. Hydrology for Engineers 1958  
 (2) Shihmen Reservoir Administration

may be subject to strong winds during the typhoon season.

#### IV. Watershed Hydrology

The Shihmen Reservoir Administration maintains eight stream gauging stations in the watershed. One station near Shihmen has kept its hydrologic data for more than 35 years.

##### 1. Stream Flows and Floods:

The annual total runoff of the watershed is 1,400 million cubic meters from a 26-year average (1927-1962). According to Yen (1961) the average size of flood of Shihmen watershed is 2,000 cms. However, during big typhoons the flood peaks may increase 4 or 5 times. The highest one ever recorded was during Typhoon Gloria. It was reported as high as 10,200 cms. from this 763 km.<sup>2</sup> watershed and the specific flow was 13 cubic meters per second per square kilometer.

##### 2. Sediment:

In comparison with other watersheds, the up-stream area of Shihmen usually

yields much less sediment. The designed annual sedimentation to the reservoir is about 800,000 m<sup>3</sup>. However, as a result of Typhoon Gloria, sediment in the 1963-1964 period was alarmingly high. It reached 19,500,000 m<sup>3</sup>, almost 24 times as high as the designed annual sedimentation. This was produced mostly by the new landslides in the watershed area.

A check dam sedimentation survey was conducted in 1962 by the Shihmen Local Development Committee. The results showed that the annual average sedimentation rate ranged from 0.6 mm. to 21 mm. Usually, check dams are built where the sediment yield is high. Table 3-4 gives some indication of the relations between land use, landslide conditions and the sedimentation rates.

#### V. Vegetation and Land Use

Approximately 91 percent of the Shihmen watershed is covered by forest. The distribution of all land use types is

Table 3-4. Sedimentation Rates of Check Dams in Shihmen Watershed

Check Dams	Date of completion	Amount silted* (m <sup>3</sup> .)	Watershed (ha.)					Annual Soil Loss** (mm)
			Forest	Farm Land	Landslide	Urban	Total	
Shui-yuan #1	May 59	34,245	123.6	36.4	0.2	1.8	162.0	21.1
Chia-tung	May 59	4,274	55.2	16.3	--	0.3	71.8	1.7
Yayu	July 59	32,612	109.7	69.3	0.3	3.2	182.5	18.0
Szeho Chiao #1	Oct. 60	1,780	26.5	21.5	--	1.6	49.6	2.0
Sanho Chiao	Oct. 60	4,325	7.7	9.8	0.1	0.2	17.8	10.5
Chiu-chi	Oct. 60	1,544	22.4	2.0	--	--	24.4	2.8
Pa-chieh	Oct. 60	2,759	17.4	5.9	--	--	23.3	5.1
San-ming	Mar. 59	6,545	113.8	146.2	--	13.6	273.6	0.6
Szeho Chiao #2	Dec. 59	950	--	5.3	--	0.1	5.4	17.6
Shui-yuan #2	June 61	1,684	52.7	1.5	--	--	54.2	3.1
San-ming #1	May 62	728	6.7	1.1	--	--	7.8	4.6
Kouka Liao	May 62	540	15.9	--	--	0.5	16.4	2.0
Average								7.4

\* Up to November 1962.

\*\* Soil loss of entire watershed above the check dam.

Sources: Taiwan Shihmen Local Development Committee.

given in Table 3-5.

### 1. Forest Land:

Forest land occupies a total area of 69,563 ha. of which 76 percent is in national forest. The remaining areas are in other forms of public lands, aborigine reservations and private forests.

The hardwood forest extends from the lower part of the watershed up to an elevation of 1,600 m. It includes principally genera of *Machilus*, *Quercus*, *Cinnamomum*, *Castanopsis*, *Cryptocarya* and *Lithocarpus*. From 1,600 m. to 2,100 m. a mixed conifer hardwood forest is found. It includes mostly *Chamaecyparis taiwanensis*, *Chamaecyparis formosensis*, *Taiwania cryptomeriodes*, *Pinus armandi*, *Pseudotsuga wilsoniana* combined with such hardwood species as *Quercus*, *Lithocarpus* and *Actinodaphne*. Above 2,100 m. elevation, coniferous forests predominate, such as *Chamaecyparis spp.*, *Pinus armandi* and *Tsuga chinensis*. *Picea morrisonicola* and *Abies kawakamii* grow at elevations of around 3,000 m.

The Taiwan Forestry Bureau is responsible for the over-all management of the national forest while one veteran's organization, the East-west Highway Forest Development Office, is governing a part of the national forest at the

southeast part of the watershed. In an effort to protect the newly constructed reservoir, logging has been allowed only to a limited extent in recent years. According to the statistics, only 303 ha. were clear-cut and 454 ha. were cut selectively from 1950 to 1962. Afforestation was started in 1900. Up to the present, there are some 4,000 ha. of artificial plantations of various ages in the watershed. The main species planted are: *Acacia confusa*, *Cinnamomum camphora*, *Pinus massoniana*, *Cryptomeria japonica*, *Cunninghamia lanceolata*, and *Phyllostachys makinoi*.

Approximately 22,600 ha. of forest land or 30 percent of the total watershed area has been designated as protection forest for water conserving purpose. Cutting is entirely prohibited on protection forests as most sites are steep and soils are thin. The fire hazard is not a serious problem in this watershed. There is no persistent dry period, the humidity is high and the winds are mild; all of these factors reduce the frequency and occurrence of the forest fire.

### 2. Cultivated Land:

Only 3.2 percent of the watershed is under cultivation, with one-third in rice paddy that presents little or no

Table 3-5.  
Land Use in Shihmen Watershed

Land Use	Area (ha.)	Percent
Forest land:	69,563.36	91.10
National compartment	53,024.59	
Aborigine forest	14,754.22	
Public forest	185.26	
Private forest	15,999.29	
Cultivated land:	2,456.29	3.25
Rice paddy	851.99	
Dry farming	1,604.30	
Denuded land:*	415.44	0.55
Other land	3,904.91	5.12
Total	76,340.00	100.00

\* Including grass and brush lands and bare land.

Sources: Taiwan Shihmen Local Development Committee 1962.

Taiwan Forestry Bureau.

erosion problem. The remaining area is used for dry land farming which creates serious soil erosion hazards. Since the establishment of a soil conservation station in this watershed in 1958, a total of 600 ha. of dry farming land has been bench terraced or protected by other kinds of conservation practices. The situation has been improved year by year.

### 3. Highway Construction:

Before the construction of the Northern Cross-island Highway there was only one highway built 15 years ago from Ta-chi to Chiao-pan-shan, 21 kilometers of this road lay within this watershed. Most of the fill slopes and cuts of this road are quite well stabilized and present no serious landslide problem.

The opening of the 50 km. Northern Cross-island Highway from Chiao-pan-shan through the southeast boundary of this watershed is now underway. It has created many landslides along its course and will undoubtedly cause more in the future.

## VI. Past Study in Landslides

In this watershed no past study of landslides has been made. The land use survey completed in 1962 did not reveal landslide as a serious watershed problem. In fact, there were very few slides in this watershed until Typhoon Gloria.

## Tsengwen Watershed

### I. General Description

The proposed Tsengwen Reservoir

is one of the most important water resources development projects in Taiwan. The dam site has been selected at the up-stream of Tsengwen Creek about 40 km. northwest of Tainan City. The total watershed area is 475.8 km<sup>2</sup> of which 98.7 percent is nationally owned.

### II. Physical Description

#### 1. Topographic and Morphologic Characteristics:

This watershed extends from the Central Mountain Range southwesterly toward the West Plain. The length of the watershed is about 41 km. while the width is 11 km. Most of the watershed is mountainous country with the highest peak in the northeast being 2,600 m. above sea level. The elevation of the proposed dam site is 110 m. With an average gradient of 1:68 the Tsengwen Creek flows 56 km. to the dam site. There are eight main tributaries and the average slope of the watershed as a whole is 28° (54.4 percent). Table 3-6 and Figure 3-5 show the watershed characteristics and topographic features of the Tsengwen watershed.

#### 2. Geology:

The Tsengwen watershed is mainly underlain by sedimentary rocks of Miocene and Pliocene age. Most of the sandstones are fine to medium grained, yellowish gray to gray in color and of moderate resistance to erosion. Shales are gray to dark gray in color, rather

Table 3-6. Morphologic Characteristics of Tsengwen Watershed

	Unit	Quantity
Total Area	Km <sup>2</sup>	475.8
Watershed perimeter	Km	121.2
Average Slope	%	54.4
Average elevation	m	963.0
Main stream length	Km	56.2
Total stream length	Km	213.1
Drainage density	Km/Km <sup>2</sup>	0.448

Source: Taiwan Forest, Water Conservancy and Soil Conservation Joint Technical Committee

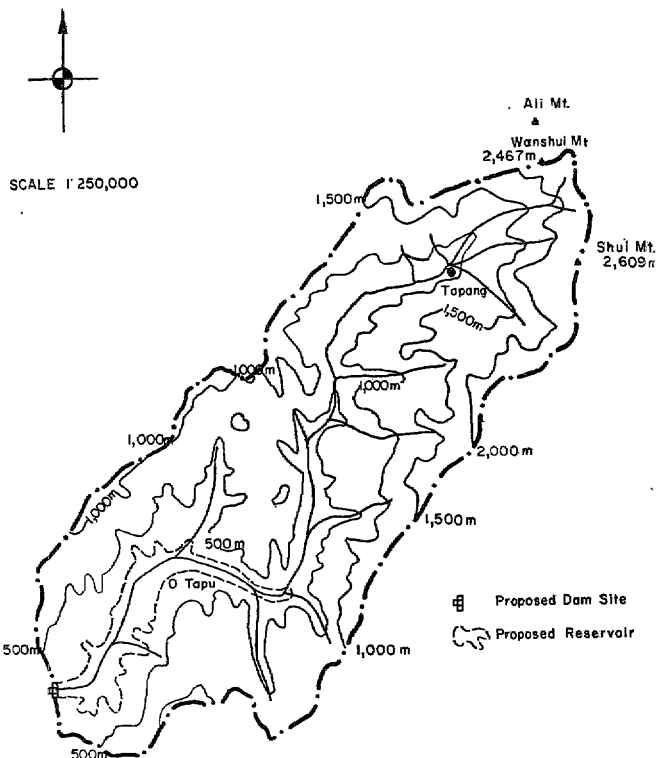


Figure 3-5. Topographic Features of Tsengwen Watershed

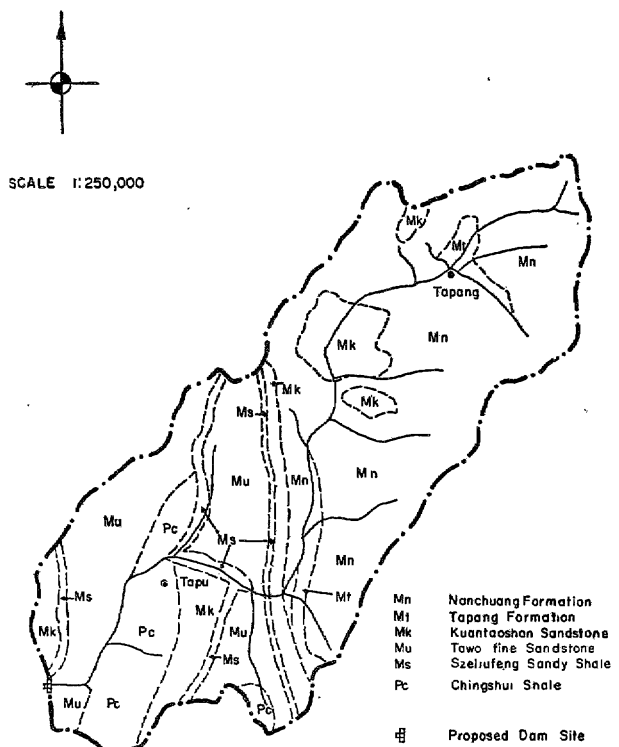


Figure 3-6. Geologic Sketch of Tsengwen Watershed  
Source: Taiwan Provincial Water Conservancy Bureau

soft and weak, and susceptible to weathering and disintegration. The distribution of these geologic formations is shown in Figure 3-6. Their general descriptions, according to Chang (1955) and to the other reports, may be summarized as follows:

- (1) Nanchuang Formation: Principally interbedded with gray sandstone and dark gray shale. At times sandstone layers are as thick as 20 m. but usually they are very thin, 1 to 2 cm. This formation constitutes the upper half of the watershed.
- (2) Tapang Formation: Yellowish gray to gray sandstones with dark gray shale interbeds. Both beds are relatively thicker than Nanchuang Formation. The Tapang Formation outcrops around Tapang Village and in the southeast corner of the watershed.
- (3) Kuantaoshan Sandstone: Fine to medium grained sandstone occasionally interbedded with shale. The colors are grayish white and dark gray. It is quite resistant to erosion and usually forms cliffs or escarpments.
- (4) Tawo Fine Sandstone: Light gray to dark gray sandstone interbedded with thin layers of shale. In some places the shale layers may be as thick as 2 to 5 m. It dominates the lower half of the watershed.
- (5) Chinshui Shale: Grayish blue shale with occasional layers of sandy shales or sandstones. This material is very erosive when wet. Most of it is concentrated in the middle south portion of the watershed.
- (6) Szeliufeng Sandy Shale: Rela-

tively fine sandy shale interbedded with grayish blue shale. It is quite erosive and is distributed in a north-south belt throughout the lower half of the watershed.

### 3. Soils

According to the survey made by the Forest, Water Conservancy and Soil Conservation Joint Technical Committee of Taiwan, there are six main soil groups in the Tsengwen Watershed as follows:

- (1) Brown podzolic soils: Well developed clay loam with 5 cm. of humus and litter on the top. A<sub>2</sub> horizon is slightly leached. B horizon is loose, soft and dark brown in color underlain with yellow brown light clay. These soils develop mostly under coniferous forests and are distributed from 1,500 m. elevation up to the headwaters.
- (2) Gray-brown podzolic soils: These soils are found from 800 m. elevation to about 1,500m. and under hardwoods and mixed hardwoods and conifers. The top soils are gray and grayish brown in color whereas the subsoils are yellowish brown. They range from clay loam to gravelly clay loam in texture.
- (3) Red-yellow podzolic soils: These soils occur from elevations of 500 m. to 1,500m. The top soils are grayish brown while the subsoils are red-yellow or yellowish brown. C horizon is newly derived from sandstones or shales. Sandy loam textures are located in the upper stream reaches and sandy clays at lower elevation.
- (4) Brown forest soils: Primarily found under humid and subtropical hardwoods up to 500 m. elevation. Top soils are loosely

structured and subsoils are quite dense. These soils are primarily sandy loams and are largely adjacent to the proposed reservoir area.

- (5) Alluvial soils: Exist only along the Tapu basin and have been developed as rice paddies.
- (6) Stony soils: They are distributed to a limited extent in this watershed, being found mostly along the steep slopes of the stream.

### III. Climate

#### 1. Precipitation:

The average annual precipitation of the watershed is 3,350 mm. with 4,200 mm. recorded upstream and 2,700 mm. close to the dam site. The principal features of the precipitation regime are typhoon storms and torrential rainfall. From October to December it is usually dry. There are 18 precipitation stations in or near this watershed. Among them, one station at Mountain Ali which is located a little beyond the north boundary of the watershed has 49 years of record. The others have average records of 10 years.

According to the Tapu Station, on the lower portion of the watershed, a 640

mm. storm was recorded in a seven-hour period during the flood of August 7, 1959. It created a new record in Taiwan. The maximum rainfall intensities of that station are as shown in Table 3-7. The Tapang station, at a much higher elevation, also had two maximum daily records, 860.5 mm. and 852.1 mm., which were among the twenty highest daily rainfalls ever recorded in Taiwan (Yen 1965).

#### 2. Temperature:

The mean, mean maximum and mean minimum temperatures at Tapang are as shown in Table 3-8. Snow may occur once or twice a year in the high mountain area and freezing is rare. There are no reliable temperature data available for the lower part of the watershed. However, according to one station beyond the southwest boundary of the watershed, the average annual temperature (37 years of record) is 25° C. The coldest month is January with an average of 18° C while July is the warmest month with an average of 29.5° C.

#### 3. Humidity and Wind:

Relative humidity records at Mountain Ali Station give an annual average of 85 percent.

*Table 3-7. Maximum Rainfall Intensities Recorded at Tapu Station, Tsengwen Watershed*

Duration	Rainfall in mm.	Date
3 hours	320.0	August 7, 1959
5 hours	554.0	August 7, 1959
7 hours	640.0	August 7-8, 1959
9 hours	697.3	August 7-8, 1959
24 hours	774.6	August 7-8, 1959
36 hours	801.8	August 7-8, 1959
3 days	892.3	Sept. 10-12, 1963
7 days	2,623.0	Aug. 31-Sept. 6 1911

Source: Taiwan Provincial Water Conservancy Bureau

Table 3-8.

*Average Temperatures of Tapang, Tsengwen Watershed*

Unit: °C

Month	Mean	Mean Maximum	Mean Minimum
January	15.7	18.2	13.1
February	15.9	18.2	13.5
March	18.0	20.5	15.5
April	19.7	22.1	17.2
May	21.6	23.7	19.4
June	22.5	24.6	20.4
July	22.8	24.9	20.7
August	22.5	24.4	20.6
September	22.2	24.3	19.9
October	20.7	23.1	18.3
November	18.8	21.1	15.8
December	16.3	19.0	13.6
Annual	19.7	22.0	17.2

Years Of record: 10

Source: Nuttinson, M.Y.1963

Because of its location and topography the effect of the monsoon wind is quite insignificant. As typhoons usually pass over north Taiwan the effect of wind is not as strong here as it is on watersheds in the northern part of the Island.

IV. *Watershed Hydrology*

1. Stream Flows and Floods:

There are three relatively new gauging stations in this watershed. In addition, a fourth station which is located beyond the watershed boundary and near the proposed dam site has maintained complete streamflow records since 1931. According to the records of that station, the annual runoff from this watershed is 1,190,000,000 m<sup>3</sup>. ranging from 300,000,000 to 2,030,000,000 cubic meters. However, from the measured floods at Shihkung station at the lower part of this watershed, and from the possible maximum rainfall, the designed flood runoff is estimated at 984,000, 000

m<sup>3</sup>. and the flood peak at the dam site is estimated 11,100 cms. The specific flow averages 23 cms. per square kilometer.

2. Sediment:

Measurement of sediment content has long been undertaken near the dam site. The average estimated sediment content is 0.6 percent and the annual volume of sedimentation is 561 hectare-meter or 5,610,000 m<sup>3</sup>. It averages 11,600 m<sup>3</sup>. per square kilometer per year.

A preliminary analysis of sediment sources has revealed that 83 percent of the sediment comes from the areas of landslides and stream bank cuttings.

V. *Vegetation and Land Use*

The major land use and vegetative cover in this watershed is illustrated in Table 3-9. Of the total, 38,200 ha. or 80 percent is presently under forest cover. Cultivated land occupies 5.9 percent whereas grassland and the other lands constitute the remaining 14 percent.

Table 3-9.  
Land Use and Cover Type of Tsengwen Watershed

Land Use	Area (ha.)	Percent
<b>Forest land:</b>	38,232	80.36
Dense natural conifer	144	
Dense natural hardwoods	23,252	
Dense plantation	2,864	
Scattered natural conifer	72	
Scattered natural hardwoods	3,100	
Scattered plantation	2,620	
New plantation	1,980	
Bamboo	3,436	
Brush	764	
<b>Cultivated land:</b>	2,796	5.87
Rice paddy	948	
Dry farming	1,576	
Orchards	272	
<b>Other land:</b>	6,556	13.77
Grassland	4,996	
Other kind	1,560	
<b>Total</b>	47,584	100.00

Source: Taiwan Agricultural and Forestry Aerial Survey Team.

#### 1. Forest Land:

Approximately 35,000 ha. or 92 percent of the total forest land is in national forest compartments of which 25,000 ha. has been designated as protection forest.

In this watershed natural hardwoods occupy most of the forest area. Their major species are similar to those of Shihmen watershed which has been mentioned previously. According to an aerial survey made in 1964 dense natural hardwood forest covers 23,252 ha. of land while scattered hardwoods constitute another 3,100 ha.

Most of the natural coniferous forests at higher elevations were cut between 1924 and 1941. In fact the north-east part of the watershed has belonged to the Mountain Ali Logging Station of the government forest agency since 1912. Practically no logging has been carried out since the end of World War II. As a result of artificial reforestation by the forestry agencies and villagers a total of 5,400 ha. of land has been re-

established in forest cover. Mostly *Cryptomeria japonica* has been used at higher elevation and *Acacia confusa* at lower mountains.

#### 2. Grass Land:

Because winter is relatively dry in this watershed, forest fire occurs approximately six times a year. From 1960 through 1963, an average of 112 ha. has been damaged annually. The 5,000 ha. of grasslands were mostly due to the forest fires in the past half century. Some burned-over areas have been planted to trees, however, some areas are hard to reforest due to the shallowness of their soil and to their inaccessibility. Most of these grasses are in *Miscanthus spp.* which have no economic value but which are providing some protection to the soil.

#### 3. Cultivated Land:

Present cultivated land constitutes 2,800 ha. or 5.9 percent of the watershed. Approximately two-thirds has been bench-terraced either for rice paddies or for dryland crops. These cultivated lands

are mostly developed on river terraces or on gentle valley slopes. They present little or no erosion hazard.

However, the remaining 800 ha. on steep slopes have serious erosion problems. They either need to be replanted with trees or require conservation treatments.

#### 4. Roads:

This watershed is quite inaccessible at the present time. There are about 15 km. of low-grade truck road across the southwest end of the watershed to connect Tapu village to the outside towns of Tainan and Chiayi Counties. Others are mountain foot paths. Erosion is not serious but since new roads are needed in the near future the landslide hazard will be greatly increased.

#### VI. Past Study in Landslides

A survey conducted in 1935 revealed that there were 770 ha. of landslides in the upper reaches of Tsengwen Watershed (Chou 1960). However, no details are available as to the actual sites and scope covered in that survey.

### Wanta Watershed

#### I. General Description

The Wanta watershed is a major upstream area of the Choshui (Muddy) River. It contributes considerable proportions of water to the power plants in the Sun Moon Lake network which generates about one-tenth of the power and electricity for the whole Island. Its water further irrigates over 50,000 ha. of paddy and cane fields in the lower plains of central Taiwan. This watershed is also famous for its contribution of large quantities of sediment to the upstream portions of the Muddy River. It is said that the Muddy River became heavily silt laden 200 years ago and the Wanta watershed was the main cause of it.

The total area of the watershed is

222 km<sup>2</sup>. and almost all the land is publicly owned, belongs either to the national forest compartments or to the aborigine reservation.

#### II. Physical Description

##### 1. Topographic and Morphologic Characteristics:

Located at the west side of the Central Mountain Range, the watershed is characterized by steep slopes, v-shaped stream valleys, high elevations and northwest orientation. Several high mountain peaks over 3,000 m. border its east boundary. Wanta Creek joins Wusheh Creek at Wanta Village where the elevation is about 1,000 m. (Figure 3-7).

Morphologically speaking, this watershed is still in its juvenile stage. The valley slope is very steep, mostly in excess of 35°. The drainage pattern is mostly dendritic. Nevertheless, at the lower part of the creek, it resembles quite an angulate pattern. An entrenched meander existing between two junctions makes the stream flow barbedly to the trunk creek, Muddy River. The average gradient of upstream is 1:35 and downstream is 1:60.

##### 2. Water Intake Pond:

A dam is located at Au-wanta for water intake purpose. The water is sent to the Wanta Power Plant downstream by a 6 km. tunnel. The thick deposition of gravel and silt along the lower reaches of this creek is partly due to the sudden decrease in stream flow caused by the diversion tunnel.

##### 3. Geology:

This watershed can be divided roughly into two geologic zones. The lower one-third of the watershed is mostly shale, slate and quartzite while the upper two-thirds is slates, quartzites and conglomerate. (Figure 3-7). All formations are of Tertiary Period.

According to the Taiwan Power

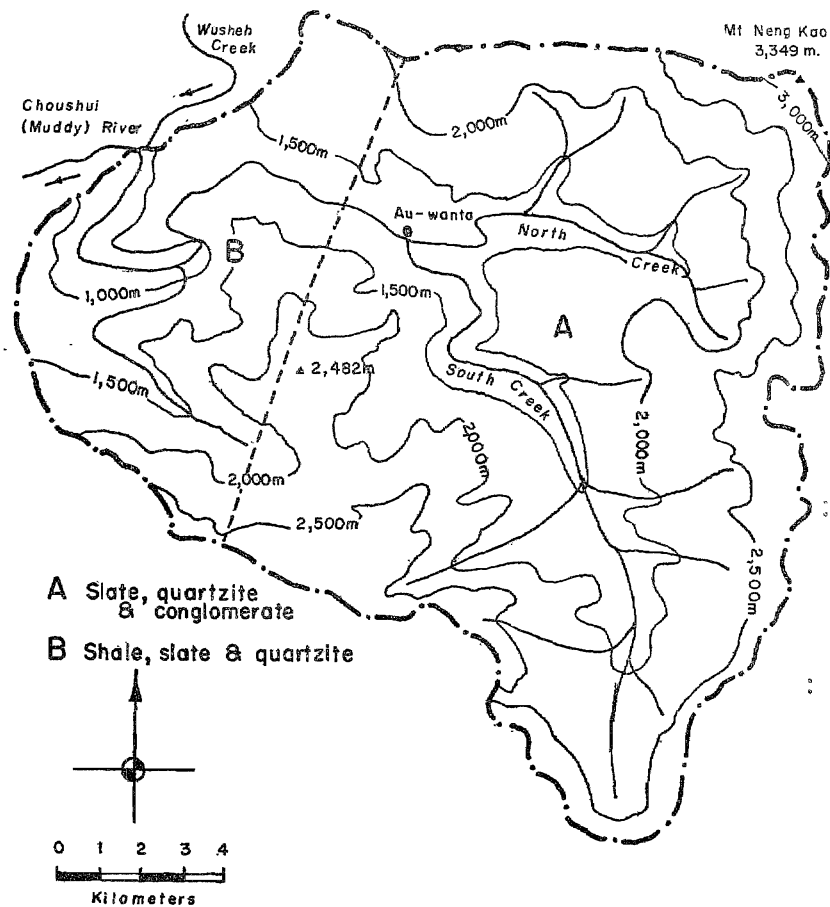


Figure 3-7. Topographic and Geologic Sketch of Wanta Watershed

Company (1951) there are four kinds of rocks common to the watershed:

(1) Clay slate: Outcropping in an extensive area in the watershed, it occurs in plates or sheets which are subject to splitting and sliding. It appears hard outwardly, but is actually soft and loose. It contains a lime substance which is easily cavitated by erosion. Areas most prone to landslides are frequently formed of rocks of this kind.

(2) Sandy slate: It is less common than the above mentioned type. These rocks are darker in color, thicker, harder and more solid. Intrusions of small quartz veins are common, making it quite resistant to erosion.

(3) Fine quartzite: This is the least common form in the watershed. It occurs in plate form and is a lighter gray in color than the slates. Sometimes it also appears in vein form penetrating into the

clay slate. Generally this rock type is quite firm, hard and solid.

- (4) Conglomerates: Conglomerates are present in the lower layer which contain particles ranging from 2 to 10 cm. in diameter. Scattered portions of sandy limestones can often be seen.

#### 4. Soils:

The majority of the soils in this watershed are dominated by stony, gravelly or skeletal soils with effective depths of less than 30 cm. Mostly belong to the Chiayang series. A description by Ru and Hua (1947) of the Taiwan Agricultural Research Institute is as follows:

0-30 cm: Yellowish brown in color with yellow mottling. Sandy clay loam. Hard subangular blocky. Abundant root hairs.

30-80 cm: Yellow with slightly gray color. Clayey texture and weak subangular blocky structure. It includes abundant slate debris.

> 80 cm: Yellowish gray. Mostly slate debris with few soil particles. Structurally weak, subangular blocky.

These soils are very susceptible to erosion, especially when the steep slopes are cultivated or burned, or when vegetative cover is otherwise disturbed.

### III. Climate

#### 1. Precipitation:

The average annual rainfall recorded (1951 to 1955) at Au-wanta precipitation station in the lower part of this watershed is 2,380 mm. The yearly maximum is 3,045 mm. and minimum 1,785 mm. Since the elevation of this station is only 1,200 m., the basin average should be much higher than recorded. The monthly distribution of rainfall is as shown in

Table 3-10.

The average annual number of rainy days at Au-wanta station is 165. Two-thirds of this precipitation is concentrated from March through August. According to its five years of record the maximum rainfall in one day is 212 mm; in two days, 322 mm; and in three days, 424 mm. Because of the relatively short period of record these intensities are not as high as adjacent watersheds. For example, a former station at Wanta which was located just beyond the mouth of this watershed had recorded 420 mm. of rainfall on June 22, 1924 and 1,478 mm. in the month of June 1912.

Table 3-10. Average Rainfall of Au-wanta, Wanta Watershed

Rainfall: mm.	
Month	Rainfall
January	91.7
February	81.4
March	165.4
April	391.0
May	394.0
June	353.2
July	306.8
August	207.1
September	121.1
October	40.3
November	116.9
December	49.4
Annual	2,381.3

Years of record: 5

Source: Water Resources Planning Commission 1957

#### 2. Temperature:

The nearest weather bureau station is located at Sun Moon Lake which is some 25 km. southwest of the Wanta watershed. The elevation of this station is 1,015 m., about 200 m. lower than Au-wanta. The average annual temperature of that station is 19.4° C. Table 3-11 shows mean, maximum and minimum temperatures by month.

As a result of the higher elevation,

the temperature in Wanta watershed is undoubtedly lower than that of Sun Moon Lake. In fact, occasional snow has occurred on the east boundary of the watershed during winter.

### 3. Humidity and Wind:

The average annual humidity at Sun Moon Lake is 84 percent with January the lowest and June the highest. In general this watershed suffers less from the winter monsoon because of its inland location.

## IV. Watershed Hydrology

One non-recording stream gauging station has been recently re-established at Au-wanta by the Taiwan Power Company. This station, which owns an upstream basin area of 148 km<sup>2</sup>, also had some records during the period of 1943 through 1950. In addition, the same Company has maintained three other stations not far below the junction of the Wanta Creek and Muddy River.

### 1. Streamflow and Floods:

The annual surface runoff at Au-wanta is 272,550,000 m<sup>3</sup>. and the daily average is 8.6 cms. The maximum mean

Table 3-11. Average Temperatures at Sun Moon Lake, Nantou County

Unit: °C	
Month	Mean
January	14.8
February	15.5
March	17.4
April	19.1
May	21.3
June	22.2
July	22.6
August	22.6
September	22.5
October	20.7
November	18.6
December	15.8
Annual	19.4

Years of record: 14

Absolute Maximum 23.5°C. Absolute Minimum 12.8°C

Source: Water Resources Planning Commission 1957

daily flow recorded on August 29, 1947 was 643 cms. from the 148 km<sup>2</sup>. of watershed. Taiwan Power Company (1951) estimated that the average speed during flood time at that part of the watershed is four meters per second.

Most flow has been diverted from Au-wanta to the Wanta Power Plant beyond the lower brim of this watershed.

### 2. Sediment:

The average annual sediment content measured at Au-wanta for the years of 1953 and 1954 was 0.6638 percent by weight. According to a report published by the Water Resources Planning Commission (1957) the maximum daily sediment transportation measured at this station was 2,190,000 metric tons on November 6, 1954. It averages 14,800 tons per km<sup>2</sup>. or approximately 1.1 cm.\* thick over the whole upstream watershed in one day!

The serious sedimentation condition can also be illustrated by the case of the Wu-chieh Dam. The Wu-chieh Dam is located about 14 km. below the Wanta watershed. According to Chu (1961), the 18,000,000 m<sup>3</sup>. of dead storage of the Wu-chieh Dam was completely filled up by river deposits only six years after its completion in 1941. Although the Wanta watershed occupies only half of the total wu-chieh basin, it was undoubtedly the main source area of sediment.

## V. Vegetation and Land Use

Forests occupy about 68 percent of the total watershed. The remaining major uses are cultivated land and inferior grassland. The distribution of these lands are indicated in Table 3-12.

\* 2,190,000 metric tons divided by 148km<sup>2</sup>. equals 14,800 tons per km.<sup>2</sup>. If 1 m.<sup>3</sup> weights to 1.8 metric ton the unit yield is 11,000m.<sup>3</sup> per km.<sup>2</sup>. Or it equals 1.1 cm. over the entire watershed.

Table 3-12. Land Use and Cover Type of Wanta Watershed

Land Use	Area(ha.)	Percent
Forest land:	15,160.0	68.17
Conifers	6,091.5	
Conifer-hardwoods	1,873.3	
Hardwoods	5,348.7	
Scattered forest	2,046.5	
Cultivated land:	1,602.8	7.21
Grassland and others:	5,477.3	24.62
<b>Total</b>	<b>22,240.1</b>	<b>100.00</b>

Source: Water Resources Planning Commission

### 1. Forest and Grass Lands:

Forest land occupies most of the upper stream area of the watershed. According to a survey made in 1950, the main types, species and their distribution elevations are summarized as follows:

#### (1) Hardwoods: (Below 2,000 m.)

*Alnus formosana*  
*Zelkova formosana*  
*Cinnamomum camphora*  
*Machilus kusanoi*  
*Quercus variabilis*  
*Quercus glauca*

#### (2) Conifer-hardwood mixture:

(2,000 to 2,800 m.)

*Pinus taiwanensis*  
*Pinus armandi*  
*Picea morrisonicola*  
*Chamaecyparis formosensis*  
*Tsuga chinensis*  
*Alnus formosana*  
*Quercus glauca*  
*Quercus variabilis*

#### (3) Coniferous forest: (2,800 m. and above)

*Picea morrisonicola*  
*Chamaecyparis formosensis*  
*Tsuga chinensis*  
*Abies kawakamii*

The forests on the lower part of this watershed were mostly destroyed by either forest fire or shifting cultivation. As a result, some 5,500 ha. along the lower valley became inferior grassland where only a few hardwoods and pine trees exist.

### 2. Cultivated Land:

In this watershed the aborigines are still using very primitive methods of cultivation. Shifting cultivation started with burning of the forest is a common practice. Very steep slopes are cultivated to row crops such as millet, peanuts and ramie, within a few kilometer diameter from the aboriginal villages. Erosion is prevalent on this kind of cultivated land.

### 3. Roads:

There is only one old road from Wanta to Au-wanta in this watershed. It is frequently damaged by stream deposition and by scouring during the typhoon season. As a result, only a part of the road is open.

### VI. Past Study in Landslides

Landslides in Wanta watershed have attracted public attention since the beginning of this century. In 1919 a preliminary survey showed that the total sliding area was 1,440 ha. in which 990 ha. were actual landslides and the remaining were cliffs along river banks and mountain slopes. It is believed ever since that this watershed has contributed most of the sediment down to the Muddy River.

A joint survey of the landslides, geologic and physiographic conditions of part of this watershed in 1950 showed that along the North Creek there were 12 big slides. The total area was estimated at 199 ha. It was also found that the sediment content of North Creek was six times more than that of South Creek after a 40 mm. storm. The total sediment transport due to landslide from these two creeks was estimated at 12,000,000 m.<sup>3</sup> in a period of 30 years.

Another survey was made in 1961 under an over-all watershed survey of the upstream basin of the Muddy River. One hundred hectares were recorded as landslides along the lower part of this watershed.

# METHODS AND PROCEDURES

## Basic Assumptions and Hypotheses

### I. *Basic Assumptions and Hypotheses*

Landslide study has long been a subject of interest for many geologists and engineers. Geologists usually emphasize the academic study of the natural phenomena whereas engineers pay most of their attention to the study of artificial slopes and soil mechanics. Not many persons, however, in other professions are interested in this subject, especially with regard to classification.

For watershed managers, landslides offer as great a challenge as other deteriorating processes which impair water quality or reduce water usage. A new landslide classification, based on the watershed management point of view, may be needed for reconnaissance type of survey and for future treatment. This kind of classification should fit the following requirements:

- (1) The classification scheme could be used for both natural and artificial slopes.
- (2) It should be so designed that both field investigation and airphoto interpretation and delineation could easily be applied or adapted.
- (3) The classification could be employed to obtain basic information for future treatment.

Because many watersheds are relatively inaccessible and landslides may occur at a great number after a storm, a much longer time would be needed to complete a survey with a complicated classification. Since the time for this kind of survey is always limited, the classification should be simple and clearcut. The use of aerial photogram-

metric technique also calls for a simple classification scheme. In case the landslide is not accessible the air photo delineation may become the only means of obtaining the necessary information.

In densely populated country like Taiwan where landslides are frequently disastrous, the demand for treatment is always high. It seems imperative that the survey classification should be designed to secure basic information for both remedial and preventive treatment rather than for purely academic study.

In view of the above mentioned conditions, landslide classification based primarily on "immediate causes" may best serve the purpose. The basic assumptions of using "immediate causes" are as follows:

- (1) They may serve as the key factors for classifying any landslide.
- (2) They may provide the bases for possible correction and treatment.
- (3) They are more easily identified in the field than other factors involved in a landslide.

#### 1. Immediate Causes as key Factors:

Many landslide classification criteria have been discussed previously in the chapter on "Review of Literature." As stated before, most of the existing classifications have their own merits as well as deficiencies. Unfortunately they are usually complicated. Some may be good for detailed study or academic research but they may not be suitable for large area reconnaissance surveys with limited budget, time, and personnel. As Cleaves (1961) has pointed out "The majority of slides require only a reconnaissance type investigation rather than

a detailed one." In order to obtain a sufficient number of observations in the most economic way the classification must be limited to a few key factors.

The present land capability classification in the United States can be used for illustration. The land capability classification is based on the degree of limiting factors rather than on detailed physical or chemical properties of soils. Such single factor as "slope" may play a very important role in the classification. In fact, "slope" and "soil depth" practically serve as the key factors in determining land capabilities in Taiwan.

Landslides can be, in like manner, classified by key factors. As discussed in the literature review, every landslide, whether on artificial or natural slopes, must have one immediate cause which dominates the others.

### 2. Immediate Causes are Bases for Treatment:

From the watershed management standpoint immediate causes are what we really need to know. As Noguchi (1963) has pointed out, such classification will provide the kind of information which will help in the programming of the control projects. Factors other than immediate causes may also be important but they are subordinate in the management program.

By removing the immediate cause (or causes), the landslides can thus be stabilized. It is the immediate cause that provides the basis for possible correction and treatment.

### 3. Immediate Causes are Easy to Identify:

To distinguish landslides by types, movements, material, mechanics and moisture contents is a laborious work and usually requires great precision. Since landslides are investigated

after their occurrence and the process involved in their initiation are usually complex, classification by "type" or "movement" is not easy. Even classification by "material" presents a problem. As Cleaves (1961) has mentioned, "The distinction between soil and rock is not always clear." No standards have ever been set for water content of the landslide material. Time may also remove some field evidence that is essential to a delicate classification. Consequently, an investigator can hardly tell a mudflow from an earthflow or a debris-slide from a debris avalanche.

Immediate causes can be easily identified by both field investigation and airphotos. The way of field identification will be discussed in the latter section "Methods of Field Investigation." Even using airphotos alone these causes are readily comprehensible. Liang (1952) in his Ph. D. thesis has demonstrated methods of identifying stream cutting, seepage, surface water erosion and toe excavation by airphotos.

## II. Tests

A few important hypotheses which may provide better understanding of landslide occurrences are to be tested. It is hoped that they will also serve as the basis for treatment as well as guides for future management.

The main objective is to test whether this proposed classification can reflect landslide problems in relation to causes, land uses, and physiographic conditions of a watershed. Further tests are to be made to the validity of using some factors to predict the landslide sizes and volumes.

### Classification Criteria

A landslide classification criterion was firstly drafted and suggested by the writer in the landslide investigation at Shihmen watershed

in December 1963 (Sheng 1964 and Chinese-American Joint Commission on Rural Reconstruction 1965). Many other participants in that and later surveys helped in the development of the criterion. It is a coincidence that "immediate causes" are also used as the foundation of the criterion which Koide (1955) and Noguchi (1963) have presented in Japan. This may be due to the fact that both countries are densely populated and the demand for landslide treatment is usually high.

### I. Immediate Causes

The first criterion used at Shihmen watershed consisted of only five immediate causes and their combinations. These initial criterion expanded into six immediate causes and their combinations when applied to other watersheds. At present these six causes plus the combinations of them have been used satisfactorily in many investigations. They are:

- (1) Runoff concentration
- (2) Stream cutting
- (3) Seepage
- (4) Road excavation
- (5) Cultivation
- (6) Geologic causes
- (7) Combined causes (combinations of the above)

Most of these factors have been discussed in the "Review of Literature." It is not necessary to repeat this discussion here. Other factors are quite self-explanatory. The identification of these causes will be explained in the next section "Methods of Field Investigation."

### II. Subordinate Factors

Besides the immediate causes many

other subordinate factors are also included in the survey as follows:

- (1) Location and elevation
- (2) Aspect: Eight aspects are considered namely: N, E, S, W, NW, NE, SW and SE
- (3) Slope: expressed in degrees
- (4) Bedrock and soil
- (5) Size and volume of slides
- (6) Land use: This includes dryland farming, terrace, rice paddy, orchard, natural forest, forest plantation, bamboo, road, grassland, plantable denuded land, unplantable denuded land and brushland.
- (7) Related phenomena: Sliding material that has been washed out or is still deposited on site.
- (8) Age: New landslides or enlarged landslides.
- (9) Landslide stability: Relatively stable, unstable, highly unstable.
- (10) Treatment: A. needed immediately, B. needed eventually, C. not needed, and D. not justified or feasible.
- (11) Treatment recommendations: Included are considerations of benching, diversion, wattling, reforestation, grass seeding, drainage, removal and clearing, installation of retaining walls, cribbing, revetments and check dams, etc.

A set of symbols and a table form have been developed (Figure 4-1) for the classification. However, the present classification is preliminary in nature and serves as a initial or feasibility criterion. It is subject to modification and improvement as more experience or research results are obtained.

\_\_\_\_\_ Watershed Landslide Classification and Investigation Form

Date: \_\_\_\_\_  
Investigator: \_\_\_\_\_

Code No.	Sub-Watershed	Elevation	No. of Map and Photo	Aspect	Symbols
Site	Slope _____, Bedrock _____, Soil _____				Other information:
Volume	Width _____ M,	Length _____ M,	Depth _____ M	Volume _____ M <sup>3</sup>	
Land Use	Dry farming(CD) _____, Terrace(T) _____, Rice paddy (CP) _____, Orchard (O) _____, Natural forest (F) _____, Tree plantation (FP) _____, Bamboo(B) _____, Road or highway (H) _____, Grassland(G) _____, Denuded, plantable (LP) _____, Denuded, unplantable(LU) _____, Brushland (J) _____,				
Immediate Causes	Runoff Concen. (R) _____, Stream cutting(S) _____, Seepage (Sp) _____, Road excavation (Ex) _____, Cultivation (Cu) _____, Geologic causes(Ge) _____,				
Phenomena	Wash out (W) _____, Deposit (D) _____,				
Age	New landslide(N) _____, Enlargement(E) _____,				
Stability	Relatively stable(St) _____, Unstable(Un), Highly unstable (V) _____,				
Treatment	Needed immediately(A) _____, Needed eventually(B) _____, Not needed(C) _____, Not justified or feasible(D) _____,				
Treatment Recommendations	Retaining wall etc. (Re) _____, Diversion (Di) _____, Bench terracing(Be) _____, Wattling (Wa) _____, Reforestation(Rf) _____, Grass seeding(Gr) _____, Check dam(Ck) _____, Clearing(Cl) _____, Drainage(Dr) _____,				
Sketch or photograph:					

Figure 4-1. A Typical "Landslide Classification and Investigation Form" Used in Taiwan



*Plate 4-1. Landslide caused by runoff concentration.  
Gullies and scars can be seen at top right.*



*Plate 4-2. Landslides caused by stream cutting. Many slides  
occurred at the maximum curvature of the meander.*



*Plate 4-3. Landslide caused by seepage. Darker tone of soil at left indicates impermeable material and high water content.*



*Plate 4-4. Landslide due to geologic causes. Note the beds dipping parallel to the slope. There is no indication of runoff concentration or stream cutting.*

## Methods of Field Investigation

### I. Preparation

Before going into the field the following work should be prepared:

- (1) Acquire or prepare airphotos. Interpret the distribution, size, slope, and accessibility of the landslides.
- (2) Collect available data and maps covering such phases as topography, soils, geology, forest cover and land uses. Utilize county maps, national forest compartment maps and all related reports.
- (3) Check needed instruments and equipment.
- (4) Prepare a landslide table form. A typical "Landslide Classification and Investigation Form" used in Taiwan is shown in Figure 4-1.
- (5) Organize an investigation group. Each group preferably should include one geologist, one soil scientist, one engineer and one forester or conservationist. Designate one of the participants as group leader.
- (6) Work out an investigation plan and set up a budget.

### II. Training

All members of the investigation group (or groups) need to be familiar with the classification scheme and the working area before they go to the actual field work. Usually one or more days of on-the-spot training is needed. This kind of training is given by more experienced personnel using pertinent airphotos and maps.

When all members have received sufficient briefing and practice to minimize classification error, the training is then considered to be complete.

### III. Investigation

#### 1. Identification of Immediate

Causes:

As previously emphasized, identification of the immediate causes is our primary objective. The distinction among different causes are as follows: (also see Plate 4-1 to 4-4)

- (1) Runoff concentration: Landslides occur due to apparent surface runoff concentrated from above. Usually there is a drainage area of considerable size above the crown or lip of the slide. Many gullies or scars can be seen feeding into the slide. A concave mid-slope is likely to exhibit these conditions. Landslides due to gully expansion also belong to this category. They may be easily identified from both airphotos and field surveys.
- (2) Stream cutting: Landslides occur because of the cutting action of a stream at the toe of the slope. In most upstream watersheds in Taiwan the valleys are V-shaped and there are almost no flats along the bottom. Wherever the stream cuts the toe of the slope, potential landslide develops. Almost all slides of this type are along streams and most of them occur at the curvature of the stream. They are dominant at the lower slopes along the stream. The crown of the slide, in general, may not extend too high. Airphoto delineation or field surveys can readily distinguish this type from the others.
- (3) Seepage: Landslides which caused

by subsurface or ground water seepage force are usually found where permeable material is underlain with an impermeable layer of soils or rocks. Or, they may occur where the water table is high. The presence of water, the existence of certain soils and rocks such as shale and fine clay beneath the area, and the irregular surface of the sliding mass will indicate this causative factor. On the airphotos, the seepage area is always characterized by a darker tone.

(4) Road excavation: Here, slides occur due to the removal of the toe of the slope or due to the overburden of excavation material on a fill slope. These kinds of slope failure are quite obvious at the time of field survey as well as in photo delineation. However, care should be taken to distinguish between the presence of mining wastes and the evidence of this kind of fill slope failure when airphoto alone is used. Usually the latter will show a definite crown.

(5) Cultivation: Landslides caused by gully erosion resulting from abusive cultivation on the slope or by percolation water from rice paddies. Landslide hazard may increase in dryland farming when steep slopes are cultivated without application of conservation measures. The identification of this type of landslide presents no difficulty.

(6) Geologic causes: Landslides due to earthquake shocks, joint

failures, extremely soft and weak formations, or at places where the beds dip parallelly to the slope, all are rated as geologic causes. The latter three cases are not difficult to identify when material and geologic conditions are examined. However, the first case needs some local information. Since large earthquakes are known and felt by everybody on the small island of Taiwan it is usually not too difficult to identify such cases.

Sometimes in identifying geologic causes, a somewhat negative approach could be used. That is, if none of the previous immediate causes could be found, this one is likely to be employed. The word "geologic" here includes both geologic and gravitational factors.

(7) Combined causes: It is not uncommon that a landslide resulted from a combination of the above mentioned factors. An additional category is therefore needed when two or more immediate causes are equally important. However, this should not be used if one cause is found to be dominate over the other.

## 2. Investigation Procedures:

All items in the "Landslide Classification and Investigation Form" are to be filled in one by one at the field. Consistency of procedure is extremely important. The form is designed to permit the use of check marks (✓) in order to save time in the investigation. Before filling in each item the person who is responsible for this particular item should check his conclusion verbally with other members

of the group. If everyone agrees, then this item is completed. Otherwise, discussion is needed. Since the members of a group may not come from the same organization and since further check of records may be needed, every member in the group should keep a complete record for every landslide. Procedures for completing the investigation form (see Figure 4-1) are as follows:

- (1) Code number: Every landslide is given a code number. The same number should be assigned on airphotos and on topographic maps.
- (2) Location and elevation: Again use both airphotos and maps.
- (3) Aspect and slope: Use compass for finding aspect and hand level for measuring slope.
- (4) Bedrock, soils and land use: The geologist and/or the soil scientist should be responsible for bed rock and soil information while the forester or conservationist is responsible for information on land use and vegetation.
- (5) Size and volume: Use tape for measuring the average width of the landslide. Length is usually estimated, using measured width as a basis. Depth is also estimated by comparing the height of trees or other vegetation. Slides at remote areas require entire estimates of size and depth as indicated on airphotos.
- (6) Immediate causes: Causes should be identified by the most experienced person. Discussion is usually needed before final conclusion is reached.
- (7) Phenomena: "Wash-out" means that all the sliding material has been washed away. "Deposit"

is that all or most of the material is left at the toe of the slide.

- (8) Age: New landslides can be identified by judging the freshness of the scar, the presence or absence of vegetation, and other available information. An enlarged landslide can be recognized in the same manner and also by contrasting old and new scars and depositions. Old landslides are excluded from this kind of investigation.
- (9) Stability: Three classes are to be distinguished: A. "Relatively stable" means no apparent, immediate danger or hazard and no indications of continuous movement. Vegetation may have re-appeared on the sliding area. B. "Unstable" means the hazard still exists. This situation may be indicated by high water content, overhanging rock or soil mass. Also, no vegetation has been re-established. C. "Highly unstable" means the landslide is still active or is under immediate danger. It may continuously slide at the time of investigation; or may be located along the maximum curvature of the stream where attacked by streamflow; it may be in an area of concentrated runoff or seepage flow; or where there is an apparent rupture.
- (10) Treatment: A. "Needed immediately" indicates treatment prescribed for those slides which will cause severe damage to villages, roads, properties, public installations, or to lives if not stopped. Cost and benefit ratios and technical feasibility should be considered in making

the decision. B. "Needed eventually" means that the needed treatment may be delayed until a more favorable time. Perhaps, economically, such treatment is of secondary importance. C. "Not needed" implies that the slide will be stabilized by itself or that little progress can be made with remedial measures. For example, where there is a thin mass over solid and resistant bedrock. D. "Not justified or feasible" means technologically or economically prohibitive.

- (11) Treatment recommendations: An estimation of the cost of the needed treatment is a prerequisite to any operation. The unit cost of various treatments are pre-determined. The cost estimation for an individual landslide is usually calculated after return from the field investigation. However, basic data such as the necessary length of a diversion ditch or the optimum area available for benching etc. should be estimated in the field.
- (12) Symbolization: A set of symbols is used for each landslide in order to show its main characteristics on maps and in table form. Symbols have been showed in the parentheses of each item in the "Landslide Classification

and Investigation Form." The sequence of symbolization is as follows:

Land use—Immediate cause(s)  
Stability—Treatment—Recommendation

Combination causes or treatments can be expressed by putting two symbols together. The whole set of symbols, for example, is as follows:

F—R ;  
Un—A—Di.Rf means:

Natural forest—Runoff concentration  
Unstable — needed — Diversion and  
Immediately reforestation

- (13) Other information: Other information and pertinent remarks are recorded whenever needed.
- (14) Sketching or photographing: Sketches or photos are made when necessary.
- (15) Copies: Each card is a record of a particular landslide. After the field investigation a master copy should be filed by the responsible agency and additional copies are to be reproduced for analysis, mapping and reporting.

Some of the above-mentioned procedures can be much simplified during field surveys by using information pre-interpreted from airphotos. Also, most calculating is to be done in the office when the basic information is obtained from the field investigation.

## APPLICATIONS AND RESULTS

### Field Applications

Field applications of the landslide classification have been carried out in three watersheds at different periods of time. The first survey was conducted at the Shihmen watershed from December 4 through December 18, 1963. At that time the writer was designated as the team leader and initiated the use of this classification criterion. The second survey was carried out in Tsengwen watershed in the summer of 1964. The writer started the survey from May 21 to May 28 and also conducted an on-the-spot training during that period. The work was then carried out by a survey crew organized from different government agencies. However, technical assistance was continuously extended by the writer during the whole survey period. The last survey was completed in the Wanta watershed in the spring of 1965 when the writer was studying at Colorado State University. However, he initiated the survey by lecturing at a training class in November 1964 and by demonstrating classification technique in mid-December, 1964.

Lately the same kind of survey has been extended to the upstream watersheds of Choshui (Muddy) River Basin and Wu (Black) River Basin covering approximately 3,100km.<sup>2</sup> Because those data are only partially available, analysis or study is not feasible. Consequently data analysis and result discussion will be limited to the above mentioned three watersheds.

Since the landslide classification scheme is preliminary in nature and continuous improvement is essential, some deviations have been made since the first survey was conducted at Shihmen watershed. For instance, the Shihmen survey was conducted after a very intense rainfall

brought by Typhoon Gloria in September 1963. Almost all of the landslides were created by the heavy rain so that the "geologic causes" were not taken into consideration in the classification. On the other hand the survey at Tsengwen watershed was carried out a few months after a disastrous earthquake which originated in this watershed and undoubtedly triggered considerable landslides. The "geologic causes" was then added. Slope criterion also differs among the three surveys. In the Shihmen and Wanta surveys, original slopes were measured whereas in the Tsengwen survey measurement was made to the slopes after sliding. Elevation and aspect of each slide were estimated from airphotos and from 1:50,000 topographic map for the Shihmen landslides. During the Wanta survey elevations were recorded in the field. In Tsengwen watershed, aspect was recorded in the field and no elevation data was collected.

Except these minor deviations the main body of the classification scheme has been established since the Shihmen survey and has been used satisfactorily in the field. All of the field surveys have been carried out by personnel who have received the same training or have practiced in the same procedures mentioned in the previous chapter, "Methods of Field Investigation." These three surveys, therefore, are believed to have been conducted in a consistent manner.

A reconnaissance type of survey has been employed in landslide classification in each watershed. The coverage of surveyed area in proportion to the total watershed are: Shihmen 63 percent, Tsengwen 90 percent and Wanta 88 percent. As a result, 631 slides have been surveyed and classifications recorded. Table 5-1



*Plate 5-1. No. 77 landslide in Shihmen watershed. Size is  $30,000m^2$ , and volume  $60,000m^3$ . It was caused by combination of seepage and runoff concentration. This is an example of a highly unstable slide.*



*Plate 5-2. Landslide conditions along North Creek of Wanta watershed. Most of the slides here are due to geologic causes and to stream cuttings.*



*Plate 5-3. No. 46 landslide in Tsengwen watershed. Its size is  $8,910m^2$ , and its volume is  $17,820m^3$ . Cause in this example was stream cutting. The slide faces northeast and is unstable.*

Table 5-1. Summary Table of Landslides in the Studied Watersheds

Name of Watershed	Watershed Area	Percent of Area Surveyed	Number of Slides	Size of Slides	Volume of Slides
	(Km <sup>2</sup> .)	(%)		(Hectares)	(1,000m <sup>3</sup> .)
Shihmen	768.4	68	257	57.6	1,189
Tsengwen	475.8	90	178	149.5	5,807
Wanta	222.4	88	196	254.4	4,030
Total	1,461.6		631	461.5	11,026

shows the distribution of these slides. Pictures of some landslides in these three watersheds are given as Plate 5-1, 5-2 and 5-3.

### Data Analysis

Data is to be analyzed in two ways. First, analysis is made to the occurrence of slides versus immediate causes and environmental factors such as land uses, soils, rocks, slopes, aspects, and elevations. When appropriate, graphic presentations or chi-square tests are employed in order to obtain better picture of landslide phenomena. The second part is aimed at further quantitative analysis. Landslide volumes and sizes are used as dependent variables versus three numerical independent variables, namely: slope, elevation and aspect. Correlation and regression methods are tried to predict

the landslide size and volume at given conditions.

Because of the large number of records, a computer has been employed in some of the analysis work.

#### I. Occurrence Analysis:

The occurrence of landslide is more realistic and important because: (1) the number of occurrence can easily be counted at the time of the survey and therefore is subject to less investigation error, and (2) once the landslide occurs it is likely to get worse and to expand. Consequently, from the watershed management point of view, no small slides should be neglected.

##### 1. Causes and Landslide Occurrence:

The causes and landslide occurrence in the three studied watersheds are shown as follows:

Table 5-2. Causes and Slide Occurrences in the Studied Watersheds

Cause	Symbol	Shihmen		Tsengwen		Wanta	
		Number	Percent	Number	Percent	Number	Percent
Runoff concentration	R	87	33.9	24	13.5	16	8.2
Stream cutting	S	62	24.1	40	22.5	9	4.6
Seepage	Sp	32	12.4	4	2.3	—	—
Road excavation	Ex	6	2.3	1	0.5	1	0.5
Cultivation	Cu	8	1.2	1	0.5	2	1.0
Runoff con. & stream cutting.	R.S	12	4.7	64	36.0	5	2.6
Runoff con. & seepage	R.Sp	42	16.3	10	5.6	—	—
Stream cut. & seepage	S.Sp	13	5.1	14	7.9	—	—
Geologic causes	Ge	—	—	18	7.3	98	47.4
Stream cut. & geologic	S.Ge	—	—	7	3.9	70	35.7
Total		257	100.0	178	100.0	196	100.0

Some implications of the above table and of Figure 5-1 are as follows:

(1) Man-made causes: Activities such as cultivation and road excavation in all three watersheds are rather insignificant in comparison with other causes. However, it should be noted that cultivated land has occupied only 3.23 percent, 5.87 percent and 7.21 percent in the Shihmen, Tsengwen, and Wanta watersheds. There were no new roads in the latter two watersheds. The Northern Cross-island Highway in the Shihmen watershed had been only 12 percent constructed at the time the landslide survey was made. Although the percent of occurrence caused by excavation was small in Shihmen watershed it does show an increase in curve slope in Figure 5-1 as compared with the

other two watersheds.

(2) Causes by water: In Shihmen and Tsengwen watersheds most landslides occurred after heavy rainfall. Typhoon Gloria created a great many of landslides in Shihmen watershed whereas in Tsengwen watershed the new slides were mostly created by the August 7, 1959 flood. These situations are reflected in Figure 5-1 where the occurrence frequencies of these two watersheds are concentrated to such causes as runoff, seepage, stream cutting and their combinations.

(3) Geologic causes: Geologic causes are quite significant in Wanta watershed. This may be due to the very steep slopes, to the juvenile stream and to the soft and loose rock structure. Because of the location of the area neither Typhoon Gloria nor the flood

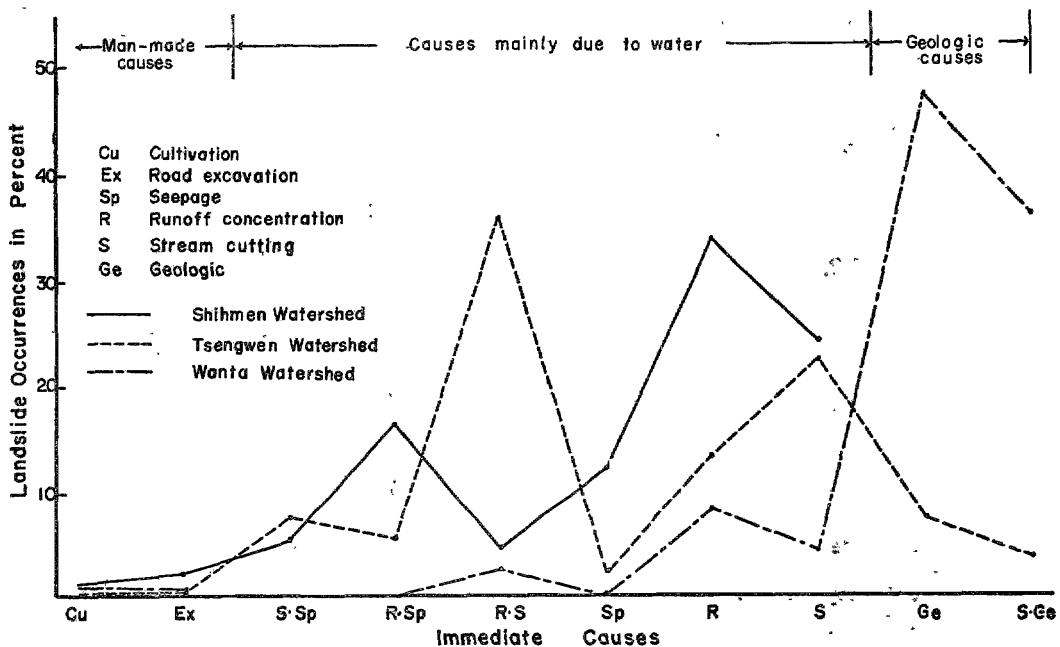


Figure 5-1. Immediate Causes and Landslide Occurrences in Three Studied Watersheds

of August 7, 1959 had major influences on the watershed. In fact the center of the past typhoons seldom passed over central Taiwan and their accompanying rainfalls were always less there (Yen 1965) .

A big earthquake which originated in the Tsengwen watershed in January 1964 created some landslides which are somewhat reflected in the curve of Figure 5-1.

It seems to the writer, therefore, that this classification does reflect the main watershed problem, whether the major cause is due to man's activity, water, or geology. Because landslides are so critical in the watersheds of Taiwan people are really concerned about their causes. By this classification scheme a clear picture of the problem could be

obtained.

## 2. Land Use and Slide Occurrence:

The land use and slide occurrence in each watershed is shown in Table 5-3.

In each watershed, landslides occur mostly in the natural forest and secondarily in grasslands. Figure 5-2 shows the relationship between major land uses and landslide occurrences in percent. It should be pointed out that, as compared with percent of landslide occurrence against the percent of land use area, the grasslands have greatest occurrence frequency than any other land uses in each watershed. As mentioned previously these grasslands are covered with inferior species and most of them were formerly cultivated or burned-over areas.

The causes of landslides in natural forests have been further analyzed in Table 5-4.

Table 5-3. Land Use and Slide Occurrence in the Studied Watersheds

Land Use	Symbol	Shihmen		Tsengwen		Wanta	
		Number	Percent	Number	Percent	Number	Percent
Dry farming	CD	9	3.5	4	2.3	—	—
Rice Paddy	CP	6	2.3	1	0.5	—	—
Natural forest	F	124	48.2	112	62.9	133	67.9
Tree plantation	FP	6	3.5	—	—	1	0.5
Bamboo	B	15	5.9	8	4.6	—	—
Road or highway	H	22	8.6	1	0.5	1	0.5
Grassland	G	54	21.0	51	28.7	43	21.9
Denuded, unplatable	LU	—	—	—	—	—	—
Brushland	J	18	7.0	1	0.5	18	9.2
Total		257	100.0	178	100.0	196	100.0

Table 5-4. Causes of Landslide Occurrences in Natural Forests

Unit: Number of Slides

Watershed	R	S	Sp	Cu	R.S	R.SP	S.SP	Ge	S.Ge	Total
Shihmen	31	38	19	2	6	20	8	—	—	124
Tsengwen	12	27	2	1	44	4	10	7	5	112
Wanta	5	4	—	—	4	—	—	66	54	133
Total	48	69	21	3	54	24	18	73	59	369

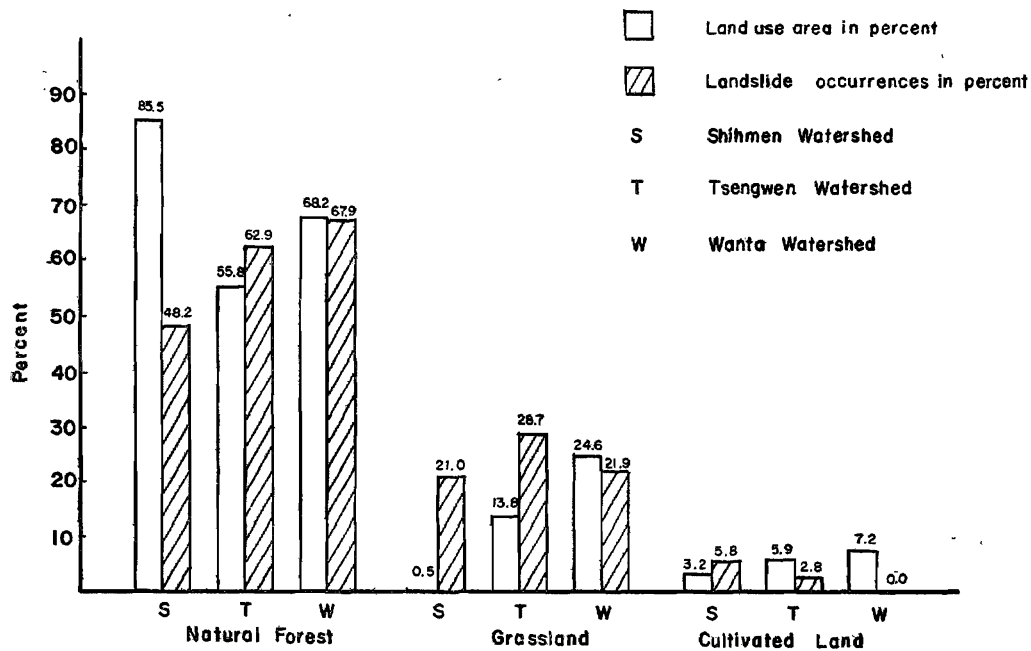


Figure 5-2 Percent of Major Land Use Vs. Percent of Landslide Occurrences in Three Studied Watersheds

In Shihmen and Tsengwen watersheds runoff concentration and stream cutting were the main causes whereas in Wanta watershed the causes were due to geologic and its combination with stream cutting.

### 3. Soils and Rocks and Slide Occurrence:

Only in Shihmen watershed was soil information recorded completely for each landslide. One hundred and forty slides (54.5 percent of the total) occurred on stony soil and 90 slides (35 percent of the total) on reddish-yellow podzolic soil. The remaining 27 slides (10.5 percent) occurred on lateritic and alluvial soils.

The rocks versus slide occurrences in Shihmen watershed are shown in Table 5-5. It shows that most of the slides occurred on slate and sandstone talus.

Table 5-5. Landslide Occurrences by Rock in Shihmen Watershed

Rock Type	No. of Slides	Percent
Slate and sandstone talus	122	47.5
Slate and sandstone	68	26.5
Sandstone and shale	29	11.2
Other talus and weathered rocks	18	7.0
Basalt and Serpentine	17	6.6
Conglomerate	3	1.2
<b>Total</b>	<b>257</b>	<b>100.0</b>

Rock types of Tsengwen watershed were divided into four groups at the time of the landslide survey. The numbers of landslide occurrence by rock type are as follows: (1) sandstone and shale interbeds 102 (57.3 percent), (2) shale 50 (28.1 percent), (3) conglomerate 13 (7.3 percent) and (4) sandstone 13 (7.3 percent). Figure 5-3 shows the

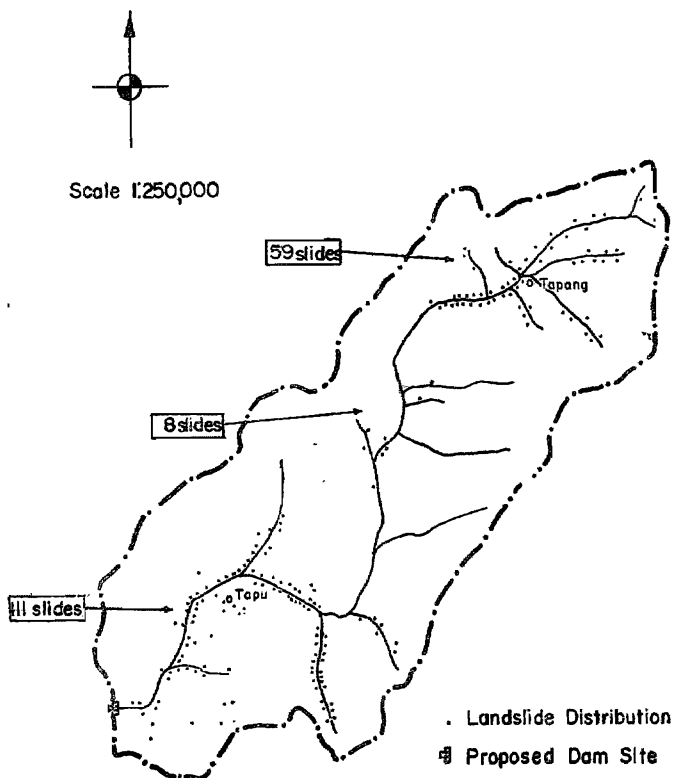


Figure 5-3. Distribution of Landslides in Tsengwen Watershed

distribution of landslides in Tsengwen watershed. It is interesting to compare this figure with Figure 3-6 and to note that most landslides occurred in Nanchuang Formation (sandstone and shale interbeds) on upstream areas, and at Chinshui and Szeliufeng shale regions along the proposed reservoir site. Only a few slides occurred in sandstone formations (Kuantaoshan and Tawo) and in the midstream area of this watershed.

In Wanta watershed almost all landslides occurred on soft clay slate which is the main rock type of the watershed.

#### 4. Aspects and Landslide Occurrence:

Statistics on eight aspects involved in landslide occurrences in the watersheds of Shihmen and Tsengwen are shown in Table 5-6. Aspect data for Wanta watershed is not available. It is interesting to note that 49.8 percent of the landslides concentrated at N, NW and W aspects, in Shihmen watershed with NW the most whereas in Tsengwen watershed 46.1 percent of the slides occurred in NE, N and NW directions (see Figure 5-4).

Table 5-6. Aspects and Landslide Occurrences in the Watersheds of Shihmen and Tsengwen

Watershed		N	NE	E	SE	S	SW	W	NW	Total
Shihmen	No.	36	31	27	36	23	12	37	55	257
	Percent	14.0	12.0	10.5	14.0	9.0	4.7	14.4	21.4	100.0
Tsengwen	No.	19	41	15	25	16	23	17	22	178
	Percent	10.7	23.0	8.4	14.0	9.0	12.9	9.6	12.4	100.0

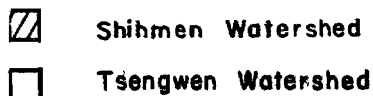
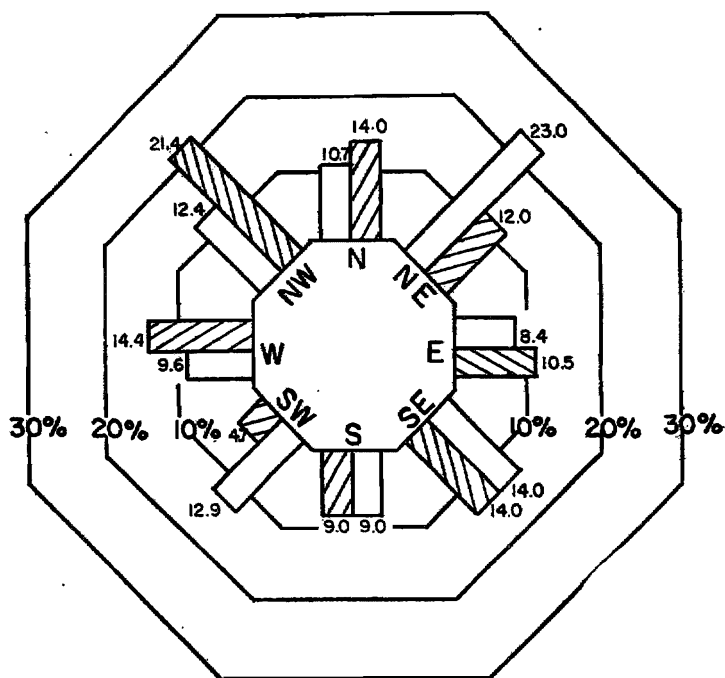


Figure 5-4. Aspects and Landslide Occurrences in Watersheds of Shihmen and Tsengwen

In investigating whether there are differences of occurrences in aspects, the Chi-square test has been employed. Assuming that landslide will occur equally at any of eight directions, the following formula is used:

$$\chi^2 = \sum_{i=1}^k \frac{(f_i - F_i)^2}{F_i}$$

Where  $f_i$  = observed no. of slides  
 $F_i$  = hypothetical number

The result of the computations for these two watersheds are shown below.

Since our computed values are much higher than the table value we reject the null hypothesis that the occurrences have no differences among directions.

#### 5. Slope and Landslide Occurrence:

Landslide occurrences by slopes on each watershed are shown in Figure 5-5 and Table 5-7.

Watershed	Computed $\chi^2$ value	Degrees of Freedom	Table Value at 0.01 Level of Significance
Shihmen	33.5211	7	18.48
Tsengwen	21.9996	7	

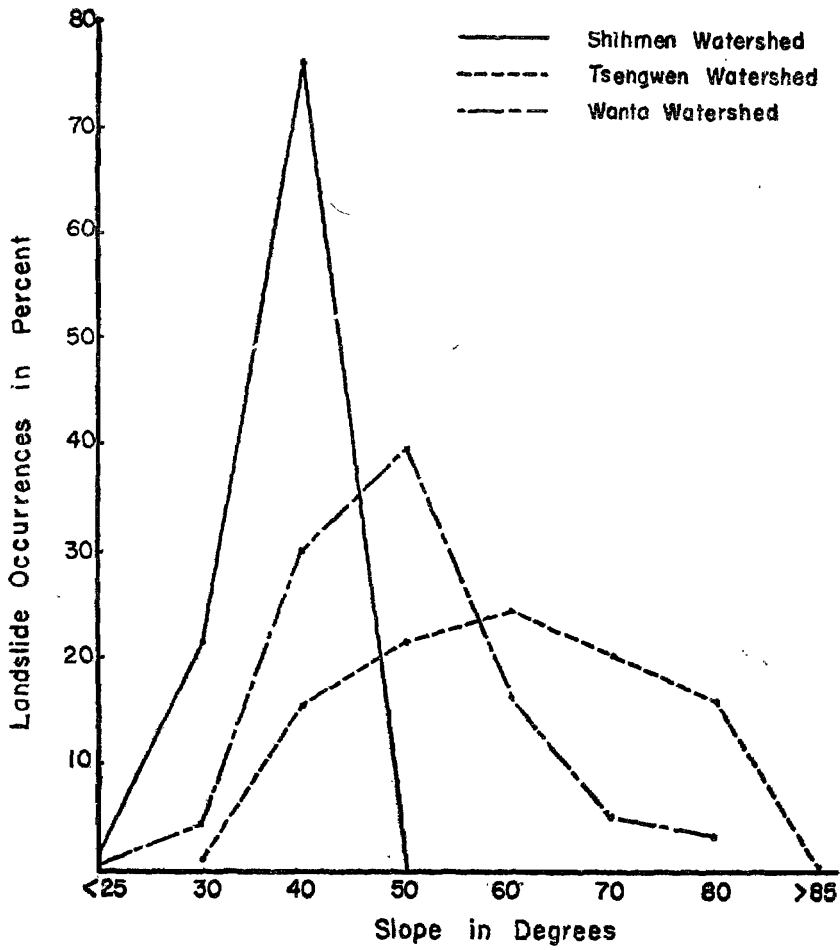


Figure 5-5. Slope and Landslide Occurrences in Three Studied Watersheds

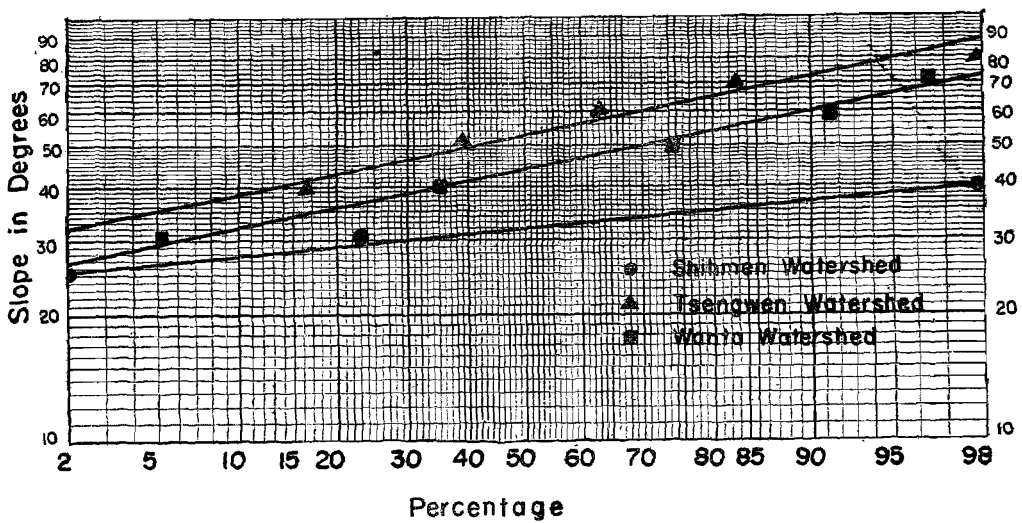


Figure 5-6. Accumulated Landslide Occurrences on Slopes in Three Studied Watersheds

Table 5-7. Landslide Occurrences by Slope in Three Studied Watersheds

Slope	Shihmen		Tsengwen*		Wanta	
	Number	Percent	Number	Percent	Number	Percent
Below 25°	4	1.6	---	---	1	0.5
25° - 34.9°	55	21.4	2	1.1	9	4.6
35° - 44.9°	196	76.3	28	15.7	59	30.1
45° - 54.9°	2	0.7	39	21.9	77	39.3
55° - 64.9°	---	---	43	24.2	33	16.8
65° - 74.9°	---	---	36	20.2	10	5.1
75° - 84.9°	---	---	29	16.3	7	3.6
Beyond 85°	---	---	1	0.6	---	---
Total	257	100.0	178	100.0	196	100.0

\*In Tsengwen watershed slope of the sliding material or scar were measured whereas in the other two watersheds measurements were made at the original mountain slope.

About 98 percent of the landslides in Shihmen occurred at slopes between 25° and 45°. In Wanta watershed, 86 percent of the slides occurred from 35° up to 65°. Only a few slides occurred below 25° in either watershed. It is interesting to see that the curves in Figure 5-5 show somewhat normal distribution shapes. Figure 5-6 shows their linear accumulative frequencies. However, more study is needed to know the relationship between slope and landslides. Slope distribution and frequency of a watershed may first need to be investigated.

Since the slopes measured at Tsengwen watershed are slopes after landsliding they appeared much steeper than the original mountain slopes. This situation is reflected in Figure 5-5 where the curve shifts to the right although the real topography of Tsengwen watershed is not as steep as Wanta.

#### 6. Elevation and Landslide Occurrence:

Table 5-8 and Figure 5-7 show the landslide occurrence in relation to elevation for the watersheds of Shihmen and Wanta. No elevation data has been collected in Tsengwen watershed.

In Shihmen watershed landslides occurred mostly at lower altitude and

the curve shows approximately negative linear correlation between occurrence and elevation. These may be due to two reasons. First, the upmost part of the watershed was not covered by the survey. Another explanation may be that most landslides occurred close to the stream. Even on the upper part of the watershed the stream flows mostly at an elevation below 1,000 meters.

The curve of Wanta watershed again shows somewhat normal distribution with greatest frequency at 1,850 m. Geologic causes (Ge) and causes of combination of geology and stream cutting (S • Ge) created many slides at this elevation.

Table 5-8. Landslide Occurrences by Elevation in Watersheds of Shihmen and Wanta

Elevation (m)	Shihmen		Wanta	
	Number	Percent	Number	Percent
200-499	93	36.2	—	—
500-799	76	29.6	—	—
800-1,099	54	21.0	7	3.6
1,100-1,399	31	12.0	25	12.8
1,400-1,699	1	0.4	52	26.5
1,700-1,999	2	0.8	62	31.6
2,000-2,299	—	—	25	12.8
2,300-2,599	—	—	18	9.2
2,600-2,899	—	—	4	2.0
2,900-3,199	—	—	3	1.5
Total	257	100.0	196	100.0

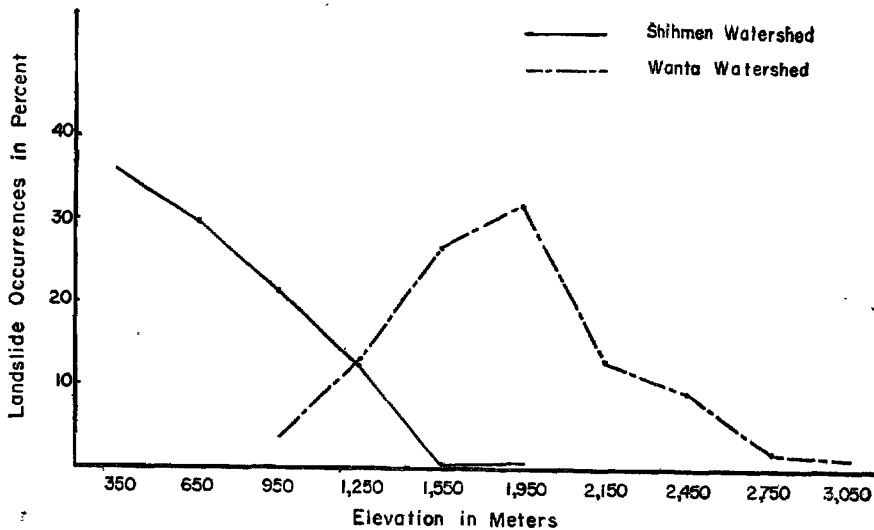


Figure 5-7. Elevation and Landslide Occurrences in Watersheds of Shihmen and Wanta

### 7. Landslide Stability and Treatment Class:

The stability and treatment classes of landslides in the studied watersheds are shown in Table 5-9 and Figure 5-8.

From Figure 5-8 we may easily see that large proportion of slides are unstable in the watersheds of Shihmen and Tsengwen whereas highly unstable conditions were found in greatest number on the Wanta watershed. As shown in Table 5-2, 83 percent of the landslides in Wanta watershed were due to geologic

causes (Ge) or to a combination of geologic causes and stream cutting (S•Ge). These highly unstable areas were extremely difficult to treat.

The stability by causes of Shihmen and Tsengwen are shown in Figure 5-9. In both watersheds, landslides caused by cultivation (Cu) were relatively stable whereas caused by seepage (Sp) and its combination with runoff (R•Sp), and caused by runoff and stream cutting (R•S) were mostly unstable.

Table 5-9. Landslide Stability and Treatment Classes in Three Studied Watersheds

Stability and Treatment	Symbol	Shihmen		Tsengwen		Wanta	
		Number	Percent	Number	Percent	Number	Percent
<b>Stability:</b>							
Relatively stable	St	16	6.2	74	41.6	46	23.5
Unstable	Un	221	86.0	92	51.7	59	30.1
Highly unstable	V	20	7.8	12	6.7	91	46.4
Total		257	100.0	178	100.0	196	100.0
<b>Treatment Class:</b>							
Needed immediately	A	51	19.8	17	9.6	—	—
Needed eventually	B	98	38.1	30	16.8	—	—
Not needed	C	13	5.1	114	64.0	64	32.6
Not justified or feasible	D	95	37.0	17	9.6	132	67.4
Total		257	100.0	178	100.0	196	100.0

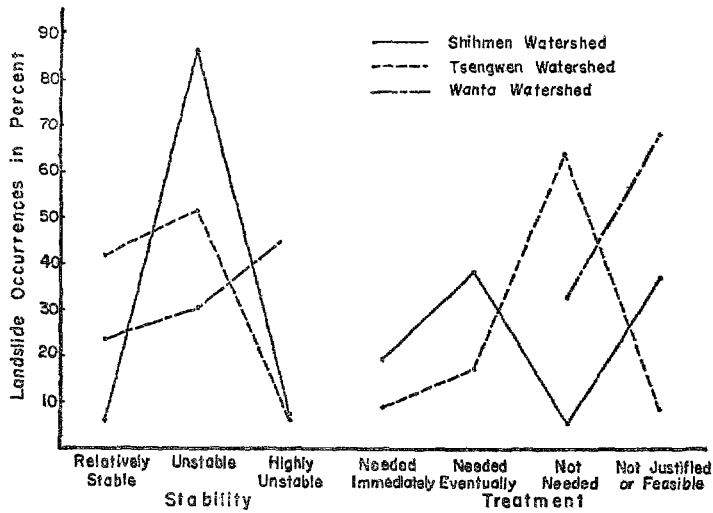


Figure 5-8. Landslide Stabilities and Treatment Needs in Three Studied Watersheds

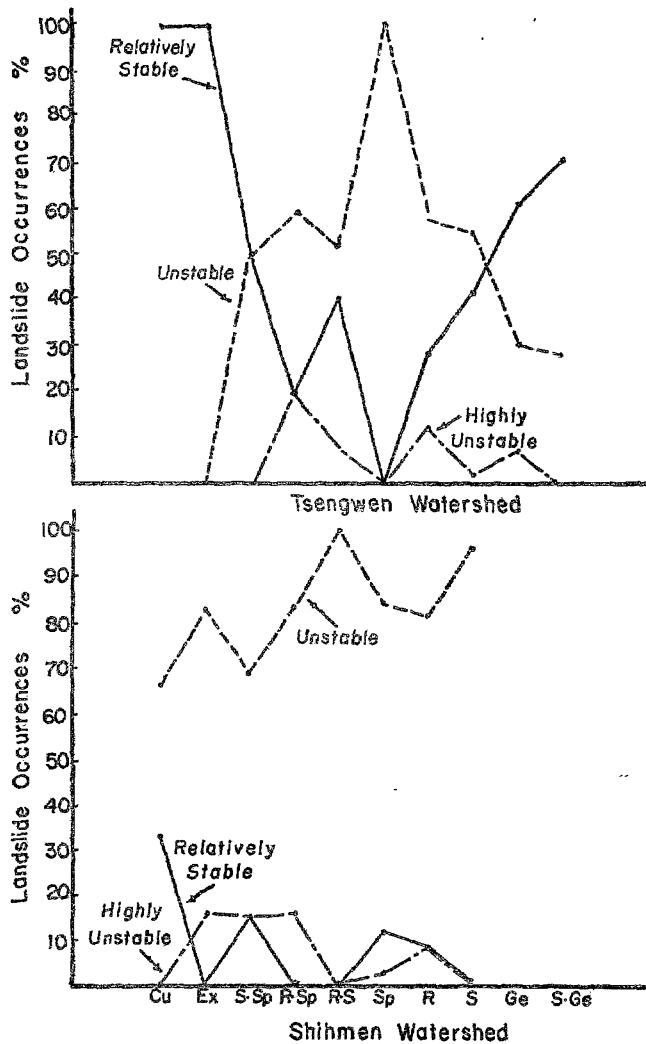


Figure 5-9. Immediate Causes and Landslide Stabilities in Watersheds of Tsengwen and Shihmen

## II. Volume and Size Analysis:

The average landslide size and volume of the three watersheds are shown in Table 5-10.

Slope, elevation and aspect are the three quantitative independent variables which can be used for further statistical analysis. In order to get a better picture and, hopefully, to obtain prediction equations between those independent

variables and the volume and size of the slides, correlation and regression methods have been employed. Hand plotting of some of the data was firstly tried out, indicating the possibilities of this kind of analysis.

Twelve sets of correlation and regression with T-tests were decided on and processed by a computer. Their results are summarized in Table 5-11.

Table 5-10. Average Size and Volume of Landslides in Three Studied Watersheds

Watershed	Average Size	Average Volume	Size per Km. <sup>2</sup>	Volume per Km. <sup>2</sup>
	(Hectare)	(1,000m <sup>3</sup> )	(Hectares)	(1,000m <sup>3</sup> )
Shihmen	0.22	4.63	0.119	2.47
Tsengwen	0.84	32.62	0.349	13.56
Wanta	1.30	20.56	1.299	20.59

Table 5-11. Results of Correlation and Regression Between Slope, Aspect, Elevation and Landslide Size or Volume

Variables①	Correlation Coefficient (r)	Regression Coefficient (B)	Y Intercept (A)	T value	Degree of Freedom
<b>Shihmen Watershed</b>					
(1) Slope Vs. Volume	+0.083	+13.77	- 14.98	0.53	255
(2) Slope Vs. Size	+0.045	+ 8.79	- 46.04	0.71	255
(3) Aspect Vs. Volume	+0.019	+ 3.28	+393.59	0.30	255
(4) Aspect Vs. Size	+0.024	+ 1.92	-218.58	0.38	255
(5) Elevation Vs. Volume	+0.350	+14.73	-532.06	4.11②	255
(6) Elevation Vs. Size	+0.247	+ 6.87	-204.95	4.06②	255
<b>Tsengwen Watershed</b>					
(7) Aspect Vs. Volume	-0.050	- 8.85	+5137.51	0.66	176
(8) Aspect Vs. Size	-0.035	- 0.80	+1004.87	0.46	176
<b>Wanta Watershed</b>					
(9) Slope Vs. Volume	+0.080	+101.93	-2674.74	1.11	194
(10) Slope Vs. Size	+0.077	+ 47.34	- 921.22	1.07	194
(11) Elevation Vs. Volume	+0.111	+ 39.57	-4879.53	1.55④	194
(12) Elevation Vs. Size	+0.130	22.32	-2651.67	1.83③	194

①Y: Volume or size

X: Slope, aspect or elevation

②Significant at a 0.01 level

③Significant at a 0.10 level

④Significant at a 0.20 level

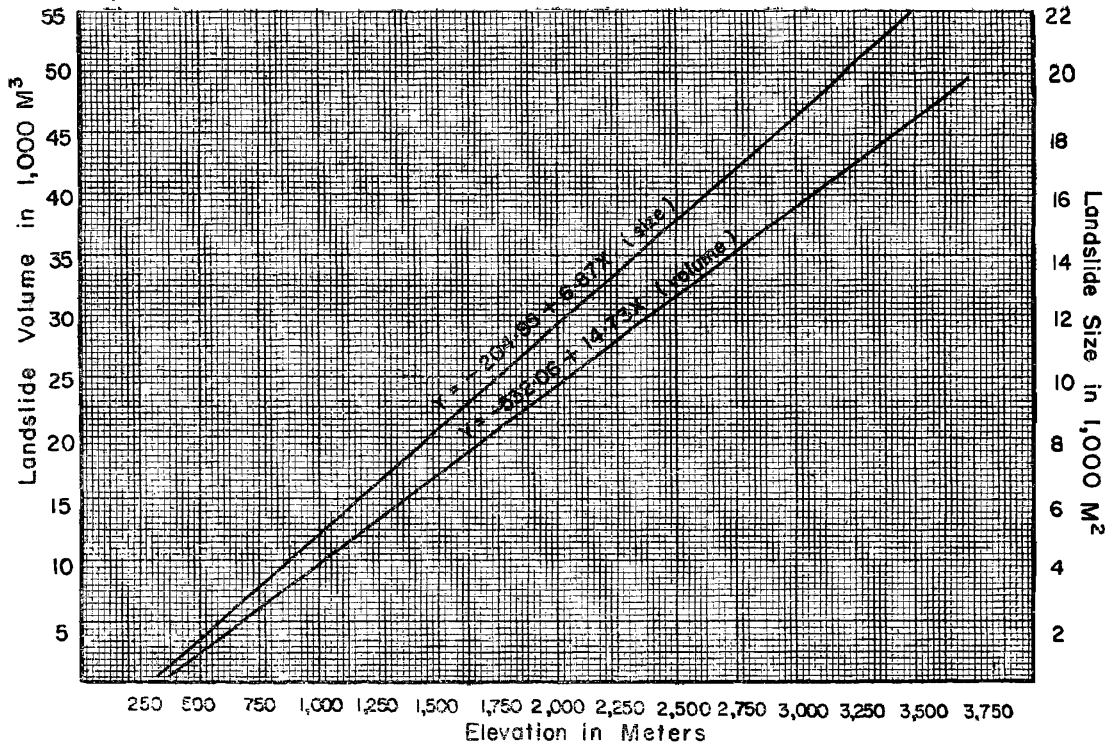


Figure 5-10. Regression on Elevation and Landslide Volume or Size in Shihmen Watershed

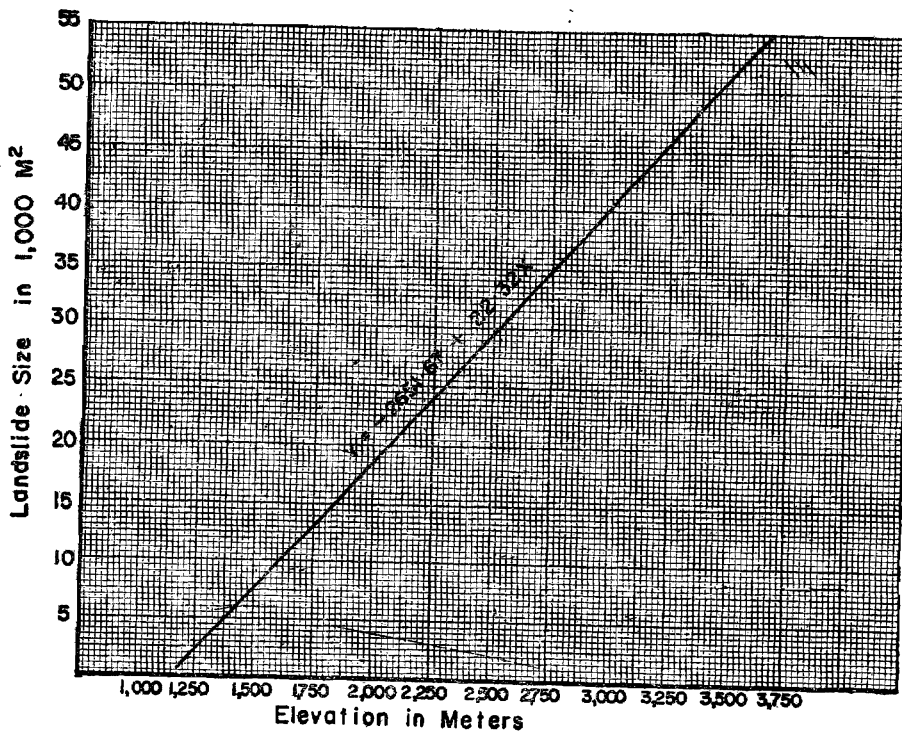


Figure 5-11. Regression on Elevation and Landslide Size in Wanta Watershed

From the above results it is found that only two sets are highly correlated. They are (5) elevation vs. volume, and (6) elevation vs. size, both in the Shihmen watershed. In Wanta watershed the correlation of elevation vs. size is more significant than elevation vs. volume. The three comparatively significant regression equations are as follows: (Also see Figure 5-10 and 5-11)

$$(5) Y = -532.06 + 14.73x \text{ (Shihmen)}$$

Where Y = Volume of slide in  $10m^3$

X = Elevation in 10m

$$(6) Y = -204.95 + 6.87x \text{ (Shihmen)}$$

Where Y = Size of slide in  $10m^2$

X = Elevation in 10m

$$(12) Y = -2651.67 + 22.32x \text{ (Wanta)}$$

Where Y = Size of slide in  $10m^2$

X = Elevation in 10m

As mentioned previously, size and volume are calculated by measuring the width and estimating the length and depth. Because the latter two factors are estimated rather than actually measured, they are subject to error. Also, the significance is only found in elevation factor, showing less encouragement on the validity of employing multiple regression. For these reasons, the writer does not intend to proceed further study on quantitative prediction. The value of the above equations can be tested in the future when more new slides occur in the respective watersheds or more study is made. However, the positive relationship between elevation and volume or size is worth further discussion and investigation.

### Discussion

The previous section has discussed some of the results along with the data analysis. Under the present section, emphasis will be given to some

specific subjects which have important implications for future management. The evaluation of both field applications and the classification criterion will also be discussed.

### I. Results

#### 1. Causes and Watershed Problems:

As mentioned before watershed problems are fairly reflected in this kind of landslide classification. The present major watershed problem in Taiwan is sedimentation. Landslides probably contribute most to this problem. As Ladd (1935) pointed out, soil erosion alone should be given less credit for playing the major role in shaping the topography. Especially in humid areas, landslides present a very serious problem.

Better understanding of the causes of landslides in a watershed will give us a clear picture of the watershed problem. The watershed manager should therefore know whether the major causes are man-made, geologic, or water-caused.

In Tsengwen watershed, for instance, analysis shows that over 70 percent of the landslides were caused by stream cutting, and by stream cutting in combination with other causes. The logical solution will be building check dams in the stream and providing bank protection. The distribution of the slides in Tsengwen watershed also shows that the critical region is centered at the upper streams near Tapang. A great portion of slides at down stream will be submerged by the proposed reservoir. If the landslide problem in Tapang area is ameliorated, the sedimentation rate could be greatly reduced.\*

On many of the hillside watersheds in Taiwan landslides are due mainly to

\*The 1964 watershed survey estimated that 83 percent of the annual sediment comes from landslides and bank cuttings.

man-made causes. Under these circumstances, preventions and cautions should be firstly emphasized on activities such as cultivation, road excavation, mining and burning. Where the causes are mostly geologic, as in the Wanta watershed, less prevention and control work could be applied successfully.

## 2. Landslides and Land Use:

People in Taiwan believe that most landslides are caused by cultivation or by logging. The results obtained from these three watersheds disapprove this point. Many landslides were found in natural forest and grassland. Possible explanations may be:

- (1) These three watersheds have vast areas in natural forests. The bigger the area the more the chance of sliding would be. Cultivation and logging occupy rather small proportions of these watersheds.
- (2) Landslides on grassland may partly account for former cultivation or burning as pointed out previously. Part of the grassland may be still subject to shifting cultivation in the future.
- (3) A considerable part of the cultivated lands have been benched for rice paddies at Shihmen and Tsengwen. These are not subject to either erosion or landslide. Water drained from upper terrace is dissipated in the lower paddy, and there is practically no seepage. Only a few cases of paddy failure were observed due to foreign runoff or stream cutting.
- (4) Aborigines in the mountain watersheds depend primarily upon farming for their living. Careful selection of sites for safe farming is therefore a ne-

cessity. A site with gentle slope, deeper and more fertile soil, and with little or no hazard of runoff concentration or stream cutting should always be used for cultivation. Such sites surely have less opportunity of sliding.

- (5) Under torrential or typhoon rains forest soils are easily saturated. Swaying of trees in wind, a large quantity of runoff from up-slope, or stream cutting at the toe undoubtedly cause landslides in forested areas. Whether tree plays a positive or negative role in causing landslide is a topic of much argument.\* It is also a very interesting and important subject for further study.

## 3. Aspect Implications:

In Shihmen watershed approximately 50 percent of the landslides occurred at north, northwest and west directions. This may be due to the influence of Typhoon Gloria. As reported by the Shihmen Reservoir Administration Typhoon Gloria which passed over the northern tip of Taiwan and stagnated from September 9 to 11, 1963, brought continuously strong northwest winds to the Shihmen watershed. As the watershed is lower at the northwest and higher at the southeast, the tremendous amount of moisture brought by Typhoon Gloria created several world records of point rainfall. The saturation of forest soils and the wind effect on trees from the northwest may have caused more landslides in the northwest aspect.

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\* Professor Endo of Kyoto University (1964) has mentioned the controversy on the relationships between forests and landslides in Japan. He pointed out that more facts and knowledge are needed to cope with the problem. Dr. E. Flaccus of the U. S. claimed (1958) that maturing forests would tend to increase slide susceptibility.

Figure 5-12 also shows that highly unstable landslides are centered around northwest direction.

Similarly, in Tsengwen watershed most of the landslides faced northeast, north and northwest. This may be due partly to the fact that the valley of Tapang and the down stream valley are east-west orientation and have more slope facing north or south (see Figure 5-3). Soil moisture conditions of north or northeast slopes may have some influences which need further investigation. However, Beaty(1956)found in the Coast Range of California that 78 out of 112 slides (70 percent) were on northwest, north, northeast and east slopes. He explained that this was because the moisture conditions necessary for landsliding occur more frequently on northerly and perhaps easterly slopes. It is also interesting to point out that Hansen (1961) found in Flaming Gorge, Utah, that the larger amount of water in the north-facing

slopes is the major factor in causing slides. If this is universally true it could serve as a guide for road planning and construction.

#### 4. Elevation and Landslides:

Analysis shows, in general, the higher the elevation the bigger the slide in both Shihmen and Wanta watersheds. In Shihmen this might be explained that the heavy rainfall created by Typhoon Gloria had a center at higher elevation (see Figure 3-3).

On the contrary, there are fewer occurrences when the elevation is high. It is especially true in Shihmen watershed. This may be due to that most of the slides occurred along the streams. It may also be due to the fact that in both watersheds a portion of the high mountain area was left unsurveyed because of inaccessibility. However, occurrences of big landslide at higher elevation should be worth attention.

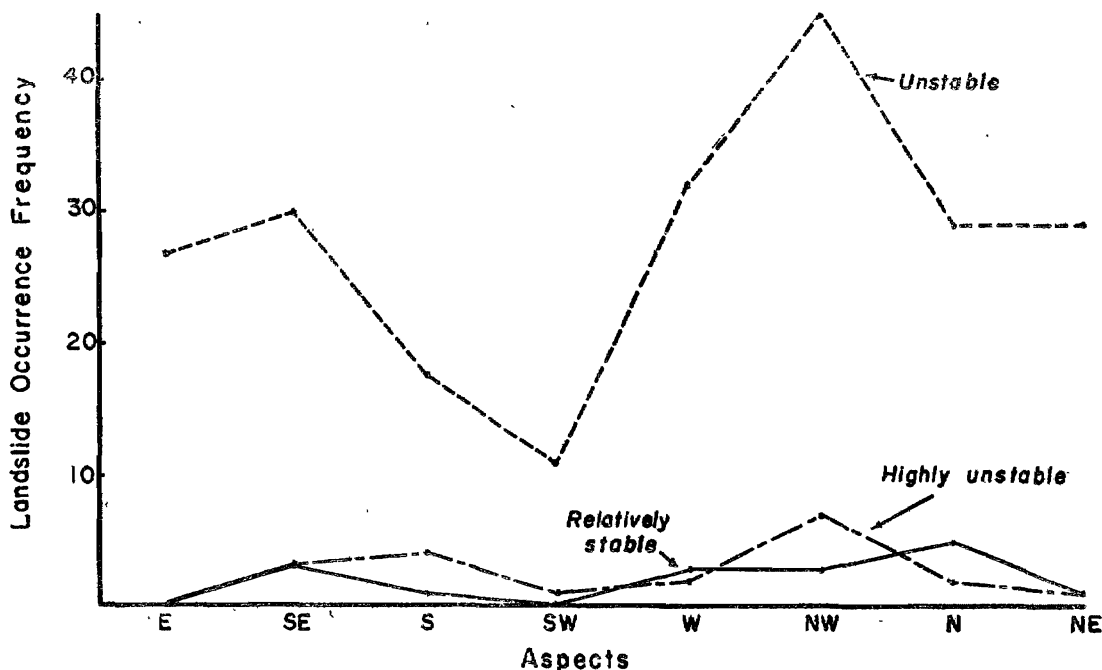


Figure 5-12: Aspects and Landslide Stabilities in Shihmen Watershed

Andre and Anderson(1961) in California found a significant relationship between the increase in erodibility and the increase in elevation. This subject also merits further study. A thorough understanding of the relationships among aspect, elevation and erodibility would provide a better basis for selecting logging road or highway locations.

#### 5. Slope Limits:

Landslide occurrences in relation to slope limits have been analyzed and briefly discussed in previous sections. Further investigation in the field is also needed in order to obtain better understanding. However, as Leopold et al. (1964) noted, "that erosion on a given slope increased to a maximum on a 40° slope and thereafter decreased to zero as the slope angle approached 90°." It is very interesting to see that Shihmen and Wanta curves in Figure 5-5 and Figure 5-6 have their relative frequency centered around 40° and 50° slopes. Also, all these curves resemble what Leopold referred to as "Horton slope function for surface erosion." In Japan, Noguchi (1963) quoted a landslide survey in which the most frequent slides were on 31° to 35° slopes. Katsumi (1964) also reported that a landslide investigation in three watersheds in Japan revealed that landslides were found most often on the slope about 40° and the distribution of landslides is normal.

#### 6. Treatment Needs:

Treatment is usually a major concern of the watershed manager or administrator. This classification has reflected the possibilities of landslide control and the treatment needs. In Tsengwen watershed, for example, 47 out of 178 slides are in need of treatment: 17 need treatment immediately and 30 need correction eventually. The total

treatment cost for these 47 slides has been estimated at 10.4 million New Taiwan dollars (U.S. \$260, 000). The needed work has also been specified. In addition, 10 check dams have been proposed as indirect or supplementary treatment. This proposal resulting from the landslide survey has been submitted to the government for action.

### II. Evaluation:

#### 1. Criterion:

The criterion of the landslide classification has been used satisfactorily in these studied watersheds. The same criterion has been and is being employed in many other watersheds of much larger area. Up to the present two big basins with a total of 310,000 ha. of mountain lands have used this criterion for classifying landslides.

However, as pointed out formerly by the writer, this criterion is by no means perfect or final. It still needs development and improvement. Some limitations and short comings of this classification are as follows:

- (1) It is good for a reconnaissance type of survey but may or may not fit the needs of academic study or more quantitative research.
- (2) Classifying "geologic causes" needs more specific explanation and experience. "Combined causes" should be used with more caution.
- (3) Some items in the "Landslide Classification and Investigation Form" could be cancelled such as phenomena (wash, deposit) and age (new landslide and enlargement). The latter is good, however, for correlations between landslides and a rare event such as a big typhoon or earthquake.

(4) The shape of slope (concave, convex or straight), slide location (middle, top or toe of a slope), and landslide in relation to bed dipping (opposite, parallel) should be added in the future investigation. All of above are easy to identify yet they are extremely important for landslide environment analysis.

## 2. Field Applications:

There has been no difficulty in applying this classification to the three studied watersheds. The investigation procedures have followed generally what the writer has described in the section, "Methods of Field Investigation." Because the criterion is still in the development stage, some modifications have been made during the surveys, thus causing some handicaps in drawing exact comparisons. For example, the slopes in Shihmen and Wanta were measured at the original mountain gradient whereas

in Tsengwen measurements were made at the slopes after sliding. In future applications, some improvements should be made as follows:

- (1) Collect enough existing data such as soil, geology, climate, etc., and study them thoroughly before going to the field.
- (2) Be familiar with topographic features, watershed morphologic characteristics, and landslide conditions by airphotos as much as possible before actual classification begins.
- (3) If possible, include a geologist and a soil scientist in the investigation group. In Taiwan, where this may be difficult, two equivalent technicians who have enough experience in soils or geologic surveys should be included.
- (4) Use air photogrammetric technique to measure the size and estimate the volume of slides.

## RECOMMENDATIONS

### Possible Treatment and Correction

In the literature review many methods of landslide treatment and correction have been discussed. Based on these, this section will offer specific recommendations for landslide control of Taiwan and will discuss the principles and philosophy governing these recommendations.

#### I. *Careful Planning and Construction of Road*

Road construction is the major man-made factor in initiating landslides in the steep mountainous watersheds of Taiwan. As more cross-island highways are to be constructed in the near future the slide hazard will undoubtedly be increased. Careful planning of highway location and supervision of construction could minimize landslides to a certain extent. It is recommended, therefore, that the Taiwan Highway Bureau and Taiwan Forestry Bureau seek cooperation with landslide experts or soil conservationists in designing, constructing and maintaining mountain roads. The Taiwan Highway Bureau especially needs to start landslide studies of its own. The experience of the Highway Research Board, Bureau of Public Roads and several state highway organizations in the United States should be of great value to Taiwan.

#### II. *Treatment of Small Landslide Area*

It is easier and less expensive to treat a landslide when it is small. After it has expanded, perhaps to five hectares, the cost becomes prohibitive and the physical operation is almost impossible.

Immediate decisions should be made as to the probable stability of the slide

and the treatment needs.

#### III. *Benching and Revegetation as Direct Treatments*

For many landslides, benching, diversion, revegetation may be used singly or in combination as direct treatments. People in Taiwan are quite familiar with bench terracing work and the labor cost is low on the Island. Protected water ways are needed to divert excess runoff to a safe place.

Vegetation grows rapidly in Taiwan because of the warm, humid climate. Once it is established it only takes three to five years to form a protective cover. Vegetation needs less maintenance than engineering structures. Revegetation, therefore, is particularly suitable for landslide treatment in mountain watersheds. However, the kind of vegetation used is a subject which needs more study. The desirable species must fit the following requirements. They should be (1) fast growing and easily propagated, (2) deep and strong rooted, (3) they should also produce a dense canopy and heavy litter and (4) should thrive on dry and infertile sites. Pine spp. may fit some of these specifications. A growth of mixed species with different layers of roots and different crown heights is highly desirable.

#### IV. *Check Dams for Indirect Treatment*

The functions of check dam have been discussed in the literature review. In places where direct treatment on landslide is not possible, check dam is often the only feasible means of indirect treatment. It is particularly good for protecting slide toes which have been jeopardized by stream cutting.

A series of low check dam is often cheaper and safer than a high dam. However, the selection of site and type of check dam to be used will involve many engineering and socio-economic problems.

#### V. *Hydro-seeding and Drainage*

Hydro-seeding has been used extensively in the United States for highway bank stabilization. The equipment contains mainly: (1) a mixer for mixing grass seed, fertilizer, and mulching material with water, and (2) a high pressure gun for shooting the mixture to the slope. Usually the hydro-seeder is attached on a truck. It is particularly good for surface erosion control. In areas of heavy rainfall, controlling surface erosion on man-made slopes may be the first step in preventing slope failure. On very steep cut or fill slopes where revegetation by manual labor is difficult the hydro-seeder offers big advantages. The most effective mulching material and seed should be determined before purchasing or making this kind of equipment.

Many landslides along highways in Taiwan were caused by improper or inadequate installation of surface drainage. Subsurface drainage systems such as horizontal pipe drains are rare in areas of serious seepage or high ground water table in Taiwan. The improvement of both surface and subsurface drainage will undoubtedly reduce landslide occurrences.

#### VI. *Immediate Causes Versus Treatment Methods*

A chart of immediate causes of landslide and suggested treatments for each is given in Table 6-1. This table lists only the main treatment methods which are appropriate under present conditions in Taiwan. All the treatments in the table have been explained in the previous sections.

Table 6-1. *Summary Table of Landslide Treatment Methods*

Immediate Causes	Appropriate Method of Treatments
R	Di, Be, Rf
S	Ck, Re(2)
Sp	Dr(2)
Ex	Re(1), Wa, Gr, Dr(1)
Cu	Be, Di
Ge	Ck

#### Remarks:

- (1) All of these symbols have been used in the "Landslide Classification and Investigation Form."
- (2) Symbols of immediate causes:
  - R: Runoff concentration
  - S: Stream cutting
  - Sp: Seepage
  - Ex: Road excavation
  - Cu: Cultivation
  - Ge: Geologic causes
- (3) Symbols of treatment methods:
  - Be: Bench terracing
  - Ck: check dam
  - Di: Diversion
  - Dr (1): Surface drainage
  - Dr (2): Subsurface drainage
  - Gr: Grass seeding
  - Re (1): Retaining wall
  - Re (2): Revetment
  - Rf: Reforestation
  - Wa: Wattling method
- (4) In case of combination causes, a suitable combination treatment will be obtained from reading across.

#### Landslide Potential

Many people are concerned about landslide potential especially such slopes along reservoirs and highways, or around residential buildings, power plants, or public installations. From the morphologic standpoint, any slope may fail sooner or later, tomorrow or after a million years.

Attempting to assess landslide potential may seem impossible to some people. It seems to the writer, however, predictions could be made by judging the immediate hazards in the

surroundings and by carefully appraising the physical conditions of a slope. Stable or unstable is, of course, somewhat relative. In most cases if there is good reason to believe that a given slope will fail in a few years or within the lifetime of a structure such as a dam, you may classify it as a slope with high landslide potential.

The real question is how to identify immediate hazards and how to evaluate physical factors such as soil, rock, slope, aspect, vegetation, groundwater table, etc. After enough data have been collected and enough samples taken, some "rules of thumb" may develop. These possibilities may be tested statistically to find the most significant factors. For instance, if landslides in a region are highly correlated to sandstone and shale interbeds, northerly aspects,  $40^\circ$  slopes, and along streams, then, you may have reason to believe that any nearby slope characterized by the above mentioned factors is probably the one which has the great slide potential. Slopes with few of

these characteristics will be safer.

With our present knowledge of landslides we cannot offer a foolproof formula for such predictions. However, due to the pressing demands from engineers of Taiwan the writer has participated in developing a preliminary scheme (Table 6-2). This scheme is being used in the proposed reservoir areas in Central Taiwan.

### Further Research Needs

The classification of landslides is only the first step toward landslide study or research. More work is needed in order to acquire better knowledge about landslide environment and causal factors. Besides some needs have been mentioned before, the followings are several subjects of study that the writer thinks appropriate for Taiwan.

#### I. Long-term Observation on Slide Development

A number of slides should be selected for long-term observation and records. Easy accessibility is essential.

Table 6-2. A Preliminary Scheme on Slope Stability Classification

Factor	A (4 points)	B (3 points)	C (2 points)	D (1 point)
1. Site	Site does not belong to B, C, or D	High ridge	Along road	Along stream or reservoir
2. Slope	$<20^\circ$	$>46^\circ$	$20^\circ-25^\circ$	$26^\circ-45^\circ$
3. Presence of sliding scars	None	Few	Some	Many
4. Soils	Medium texture	Coarse texture	Medium stony soil	Fine texture or coarse stony soil
5. Land Use or Cover	Dense cover	Sparse cover	Cultivation without conservation	Use with severe soil disturbance
Area	ha. Total Points			
Stability Class:	Stable (20-18 points)		Unstable (10-11 points)	
	Relative Stable (12-17 points)		Highly Unstable (5-9 points)	

A complete survey and investigation on topographic and other physiographic conditions is necessary at the beginning. Any later change in size and volume should be recorded and studied. If any voluntary vegetation comes up it should be identified and its cover measured. These observations should be carried out at least twice a year, one before typhoon season and one after. Observations should be continued until the slide is self-stabilized, or until enough data for reference has been secured. Additional observations should be made after a particular heavy storm. Correlation between changes in the slides and the amount and intensity of rainfall is also needed.

## II. *Photogrammetric Study on Landslides*

With enough data and experience obtained in the field delineation, photogrammetric study on landslides alone should present a fairly accurate picture. Such study, along with photogeologic study, should be much increased in order to reduce field investigation to a minimum.

## III. *Identification of Old Landslides*

About half of the landslides found in Shihmen watershed occurred on talus slopes or on old landsliding areas which had been covered with vegetation. According to Liang (1952) roads should not be constructed on such sites.

The importance of developing ways of identifying old slides is at least twofold: (1) to avoid disturbance of them as mentioned above, and (2) to intimate the conditions under which a landslide could stabilize by itself. Vegetation and geomorphic evidence should serve as a basis for such identification.

## IV. *Research on Vegetation and Landslides*

The requirement of the ideal revege-

tation species for landslides have been discussed previously. Since revegetation is probably the least expensive treatment of slides on natural slopes, research should be much emphasized in order to find the best species and the best methods of establishing them.

On the other hand, the reasons why slides occurred in areas with certain types of vegetation and did not occur in others should also be investigated. Particularly, root systems and depths should be compared.

## V. *Landslide Volume Prediction*

Volume and size prediction have been partially discussed in the section on data analysis. The choice of independent variables, the quantification of certain variables such as rock, soil and cover, etc., and the proper prediction equation of a watershed should be carefully worked out.

With records of several thousand slides now available in Taiwan and with the help of computers, it is hoped that certain reliable multiple regression equations can be worked out for predicting the volume of slides.

## VI. *Study on Regional Relation of Slides*

Landslides are mainly the products of geomorphic processes. They are most likely to occur, according to Howe, Sharpe and others, during the period of youth to early maturity. Regional characteristics in relation to landslide occurrences, therefore, are subject to more study. Baker (1959) of the United States and Popov (1963) of Russia indicated the importance of this kind of correlation.

Geomorphic features, geologic formations, climatic data and other environmental factors, such as soils, water tables, elevations and aspects etc. should be closely scrutinized and compared before a reliable conclusion can be reached.

## SUMMARY

Because of geologic youth, abundant and intense rainfall and frequent earthquakes, Taiwan suffers from severe landslides in its mountain watersheds. Landslides not only contribute tremendous quantities of sediment to the streams and reservoirs below, but also aggravate flood damages, interrupt highway communications and endanger villages and human lives. The extent of landslides in Taiwan is estimated at 40,000 hectares.

Classification of landslides is the first step toward better understanding of the problem. The ultimate goal is to reduce landslide occurrence and to treat or correct the existing landslide areas. As many new highways are to be constructed and many slopelands are to be developed in the mountain watersheds due to high population pressures, the necessity of landslide classification and study is apparent.

Under this study a new landslide classification scheme has been developed. This classification is designed to fulfill the following objectives:

- (1) To be used on both natural and artificial slopes.
- (2) To be easily applied or adapted by field investigation and aerial photo survey.
- (3) To be employed for reconnaissance type of survey which permits the investigation of a great number of slides in a limited period of time.
- (4) To be used for obtaining basic information upon which a treatment plan can be drawn.

The present scheme is based primarily upon immediate causes as follows: (1) runoff concentration, (2) stream cutting, (3) seepage, (4) road excavation, (5) cultivation, (6) geologic causes, and (7)

combinations of the above. Many subordinate factors are also included in the scheme such as slope, aspect, elevation, land use, soil, rock, size, volume, stability and treatment needs. The identification of the immediate causes and the investigation procedures and techniques have also been developed.

The proposed classification has been carried out in three mountain watersheds of Taiwan: Shihmen, Tsengwen and Wanta. A total of 631 slides have been investigated and classified. Their occurrences in relation to immediate causes and environmental factors such as slope, aspect, elevation, land use, soil and rocks are analyzed. Statistical methods and computer calculations have been employed in part of the analysis.

Some important results and findings are as follows:

- (1) In these three watersheds man's activities such as road excavation and cultivation have caused insignificant occurrences of landslides. This may be due to the fact that the cultivated areas only occupy a very small portion and there were not many roads then in each watershed. Rice paddies or careful development of sites for cultivation also tend to reduce landslide hazards. Most landslides in Shihmen and Tsengwen were caused by runoff concentration, stream cutting, or their combinations resulted from Typhoon Gloria and the August 7, 1959 flood. Geologic causes are dominant in Wanta watershed where the slopes are extremely steep and rock structures are soft and

loose. Through this classification, therefore, the main causes of landslide and major watershed problems can be fairly reflected.

- (2) An average of 60 percent of all landslides occurred in the natural forests in these three watersheds. Landslides in the grasslands accounted for 24 percent while only a few percent occurred in the cultivated lands. This may be due largely to the fact that natural forests occupy a major proportion of each watershed, usually on the steepest areas. Also to the fact that saturation of soil and the swaying of trees during typhoons tend to loosen soil mantle. Analysis has shown, however, that grassland has highest rate of landslide occurrence than any other land uses.
- (3) In Tsengwen watershed over half of the slides occurred on shale and sandstone interbeds. Apparently due to the stony soil and the slate and sandstone talus (or old slides) in Shihmen watershed, more slides occur on these soil or rock types than on any other.
- (4) About 50 percent of the landslides in Shihmen occurred at north, northwest and west aspects with the most frequent being on northwest slopes. In Tsengwen watershed, 46 percent of slides are facing northeast, north, and northwest. The former case might be due largely to Typhoon Gloria which brought continuous strong northwest wind with high amounts of precipitation to the northwestern faces of the Shihmen watershed. The latter case may be partly due

to the fact that northerly facing slopes have much greater water holding capacities which tend to make them more susceptible to sliding. Beaty (1956) and Hansen (1961) have noted similar findings in the United States. However, both cases need more study and investigation.

- (5) In Shihmen and Wanta watersheds 70 percent of landslides occurred on slopes of around 35 to 55 degrees. It is interesting to note that Nakamura (1955), Noguchi (1963), and Katsumi (1964) of Japan, and Leopold et al. (1964) of the United States have indicated similar facts that most landslides or erosion occurred in that approximate range of slopes. Slope distribution of a watershed may have a significant effect on slide occurrence. Again this factor needs further study.
- (6) Statistical analysis shows a significant linear correlation between elevation and volume or size of landslides in Shihmen and Wanta watersheds. Whether this correlation is due to the greater susceptibility of erosion and landslide at higher elevations or to the heavier rainfall received at these elevations also needs further investigation. A study by Andre and Anderson (1961) indicating a significant relationship between elevation and erodibility in northern California may serve as a good example for this kind of study.
- (7) More than 85 and 50 percent of slides in Shihmen and Tsengwen watersheds respectively were classified as unstable. In Wanta

watershed 46 percent of the slides were highly unstable. Results also show that 58 and 26 percent of slides in the former two watersheds need to be treated. In the Wanta watershed none of the landslide areas need or could be treated directly because of geologic causes and they are highly unstable. In case of Tsengwen watershed a preliminary plan and budget for landslide treatment have been worked out and submitted to the Taiwan Provincial

Government for consideration and further action.

Based partly on the results of this classification and study, recommendations about possible treatment and correction, landslide potential classification and future research needs have also been made.

Finally, the writer wishes to point out that this classification, although it has been used satisfactorily, still needs further development and improvement as more experience and research findings are to be obtained.

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臺灣河川上游集水區，由於地形多屬幼年期，雨量強度特大，以及地震關係，崩坍情形甚為嚴重。崩坍地不但產生大量泥砂淤積下游水庫及河床，並且加劇水患，阻塞交通，危害人民生命及財產。此類崩坍地，估有四萬公頃之多。

崩坍地的分類為瞭解及研究崩坍現象的第一步。最終目標在於減少崩坍機會，施行處理，使之安定。臺灣由於人口壓力關係，今後對坡地利用以及山區道路之開闢，勢必加速。因此，崩坍地的研究與分類，極為需要。

本文提出一項崩坍地分類方法，此一新方法的特點如下：

- (1)可以適用於所有坡地（自然及人工）崩坍分類工作。
- (2)無論野外調查以及航空測量均易於採用。
- (3)適於崩坍地的普查工作，尤宜在短期內完成大量崩坍地調查。
- (4)可藉以獲致基本資料，作為崩坍地處理的依據。

上述分類主要係基於崩坍近因，諸如(1)逕流集中，(2)溪流淘刷，(3)底土滲流，(4)開路關係，(5)開墾關係，(6)純地質原因，(7)複合原因等。環境因素諸如坡度、方向、海拔、土地利用、土壤、母岩、面積、體積、安定度、以及處理需要等等也包括在內。關於崩坍近因之識別，調查方法及程序等，亦有詳細說明。

此項新分類方法，曾在石門、曾文、及萬大等集水區內試用。總計調查崩坍地有六百三十餘處。崩坍處數、近因與環境因素間關係曾予分析，部份資料並以電腦及統計方法整理。茲將重要結果簡述如下：

- (1)在上述三個集水區內，人為因子如開墾及築路等與崩坍地發生關係不大。可能因開墾地所佔面積甚小，以及調查當時尚少道路。石門及曾文集水區內大多數崩坍地，均由於溪流淘刷，逕流集中及其複合原因所造成，多係葛樂禮颱風及八七水災之後果。在萬大集水區，則崩坍大多為地質原因所造成，坡度陡峻，岩石疏鬆，有以致之。概括而言，應用此一分類方法，可以大體反映崩坍原因及集水區主要問題所在。
- (2)三個集水區中，平均有百分之六十崩坍地發生在天然林內，百分之二十四發生於草地，僅有極小部份發生在開墾地內。此一現象，可能由於天然林所佔面積甚大，且坡度較陡。在颱風豪雨期間，土壤中水份的飽和以及樹木的搖動，均不無關係。唯如以草地所佔面積與林地等比較分析，則草地發生的崩坍率，較其他土地利用為高。
- (3)在曾文集水區內，半數崩山發生於砂岩及頁岩互層。石門集水區崩坍地，則多發生於石質土及板岩與砂岩堆積層。
- (4)石門集水區內約有百分之五十崩坍地發生在北、西北及西三個方向，其中以西北為最多。在曾文集水區中，百分之四十六崩坍地係向東北、北、以及西北。前者與葛樂禮颱風強烈而持久西北風不無關係。後者可能由於北向山坡土壤含水量較多，容易引起滑崩。美國貝笛氏 (C. B. Beaty) 及韓森氏 (W. R. Hansen) 均有類似發現。唯上述真相，尚需進一步探討。
- (5)石門及萬大兩集水區內，百分之七十崩坍地均發生在坡度三十五度到五十五度之間。

日本中村慶三郎、野口陽一、勝美諸氏，以及美國李奧波等 (L. B. Leopold et al.) 均曾報導大多數崩坍或沖蝕發生在類似的坡度範圍以內。此項結果甚為有趣，值得進一步研究。

(6) 統計分析顯示，在石門及萬大集水區，海拔高度與崩坍地體積或面積具有直線正相關關係。此項關係究竟由於高海拔易於沖蝕崩坍或由於雨量過大，需要進一步調查。安吉拉及安德孫 (J. E. Andrie, H. W. Anderson) 在美國加州北部所作研究，認為高海拔與土壤沖蝕度有顯著相關性，其方法可作我們的參考。

(7) 石門集水區百分之八十六崩坍地，以及曾文集水區百分之五十二崩坍地，均屬於不安定級。在萬大集水區，則百分之四十六屬於極不安定級，百分之三十為不安定級。又，調查結果顯示，石門有百分之五十八及曾文有百分之二十六崩坍地需要處理。且曾文崩坍地安定初步計劃預算，業已由有關機關呈請臺灣省政府考慮實施。至萬大集水區，由於地質原因及不安定關係，其崩坍地均屬無法處理及不需處理級。

基於此項分類調查及文獻研究結果，本文尚提出崩坍地各種處理方法及坡地安定度分級標準。對於今後試驗研究，亦有下列數項建議：

- (1) 長期觀測崩坍地移動及變化情形。
- (2) 崩坍地航測技術研究。
- (3) 古代山崩或堆積層之地形判認。
- (4) 崩坍地的植生研究。
- (5) 崩坍地定量及統計推測分析。
- (6) 地域性崩坍現象研究。

最後，作者特別聲明，本文僅在方法上提供一項實例，作為本省此方面研究之開端。由於資料不全，遠處國外，所得結果難免有管見及遺漏之處。且此項分類方法，雖然應用迄今，尚稱圓滿，日後如經驗增加，試驗有成，需要改進之處仍多。本文之作，承林淵霖先生、葛錦昭先生，以及陳信雄先生供給資料，在此表示謝意，對參加野外調查各位之辛勤努力，尤深感激！

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