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GRAVEL DEPOSITS IN TAIWAN

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GRAVEL DEPOSITS IN TAIWAN

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INTRODUCTION

The primary terrace deposits on the island of Taiwan are gravels, with distributions spread out along the western edge of the northern and central part of the island, as well as in areas between the coastal plain and foothills. Due to the rapid economic development and population growth on the island in recent years, areas of activities are inevitably moving towards slopelands and hillsides. Many highways, residential developments and industrial zones are situated on terrace deposits. Since the geotechnical characteristics and behavior of terrace gravel deposits are significantly different from those of alluvial and sedimentary deposits or rock formations, selection of methods of exploration, testing and analyses often poses problems to geotechnical engineers. The most commonly encountered problems or difficulties include:

- (1) Which method(s) is most suitable for site investigation of gravel deposits?
- (2) How to determine or analyze the slope stability of gravel deposits?
- (3) What is the bearing capacity of a gravel deposit? How much is the settlement of structures founded on this type of deposit?

Up to the present time, study of engineering behavior of gravel deposits in Taiwan can only be considered in the infant stage. Many of the basic data are still lacking. The primary objective of this paper is to present a rational approach to exploration of the engineering behavior of gravel deposits in Taiwan, on the basis of geological history, particle structure and limited engineering experience, with particular emphasis on slope stability and foundation problems. It is hoped that this paper will stimulate the interest of the geotechnical profession in the engineering problems of construction on terrace gravel deposits.

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GEOLOGICAL CONDITIONS OF GRAVEL DEPOSITS IN TAIWAN

Geologically, the island of Taiwan can be divided into three major provinces as shown in Fig. 1. In the central part of the island, the Central Mountain Range, which consists of several parallel mountain chains, runs in a north-south direction parallel to the longitudinal axis of the island. The western part of the island is occupied by coastal plains. Between the Central Mountain Range and the Western Coastal plains is the Western Foothill Province. The Central Mountain Range divides the island into two unequal parts, the western flank being about twice as wide as the eastern flank. The western flank declines from the Central Range westward into strips of foothills and then into broad tablelands and terraces. The elevation of the foothills varies from about 100 m to 600 m above the mean sea level. The majority of the broad or large tablelands and terraces are concentrated in the north-western part of the island as shown in Fig. 2. These terraces are covered with a thick layer of gravel deposit. Based on geological studies, (Ho, 1975; Lin, 1957; Lin & Chow, 1978), these gravel layers are Quaternary terrace sediments. Gravel particles and rock fragments from the Western Foothills were carried by river flow in a east to west direction and sedimented along the banks or mouths of ancient rivers.

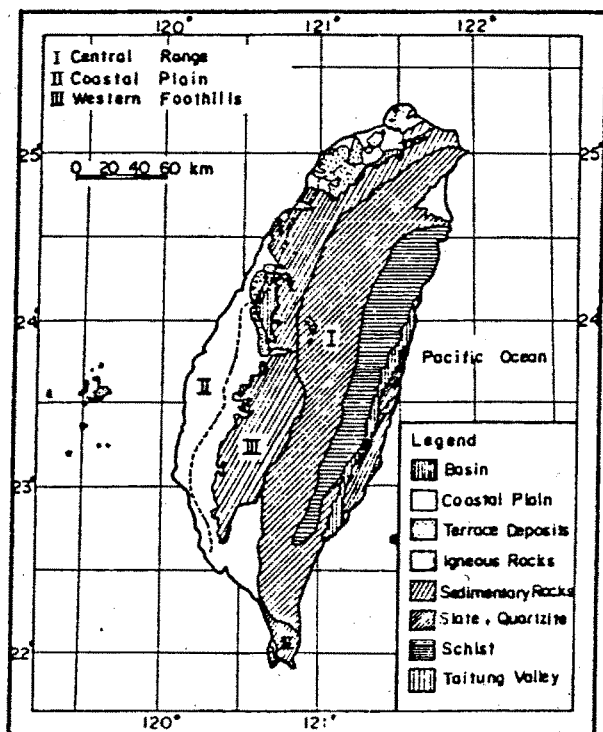


Fig. 1 Geological Provinces of Taiwan

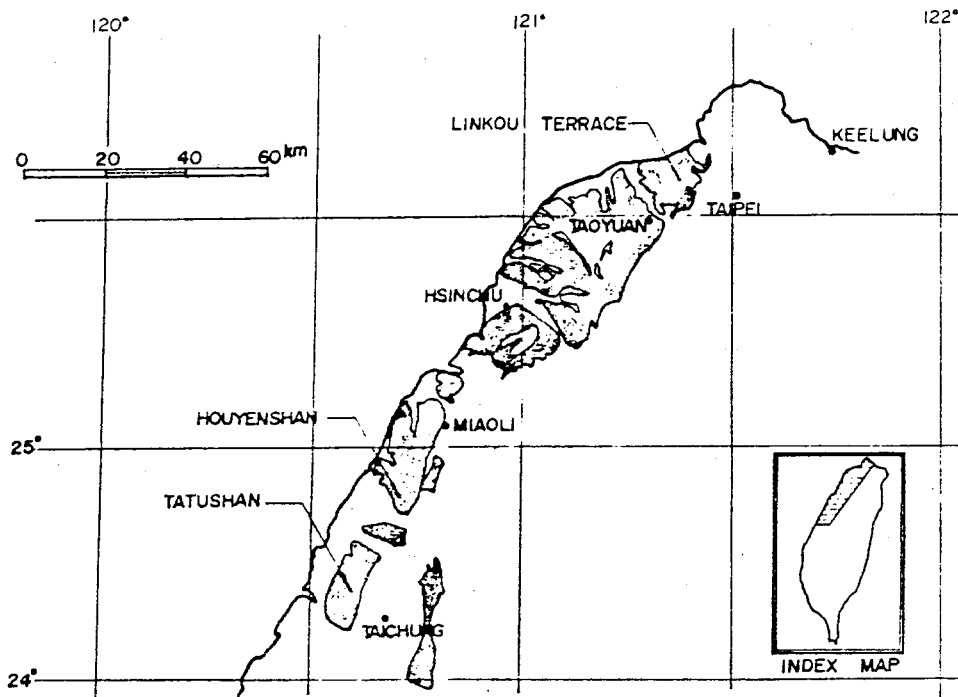


Fig. 2 Distribution of Gravel Terraces Deposit in Northwestern Taiwan

Subsequently, due to tectonic movement, these sediments were elevated and form terraces or tablelands.

At present, the majority of these gravel layers are composed of an uncemented gravel matrix infilled with sandy or silty soil particles. Above the gravel stratum, there is usually a layer of red soil of few meters in thickness. This red soil was apparently formed by the in situ laterization process. It was found that the soil infills in the gravel stratum were also affected by the laterization process and became red in color. Up to now, the geological evidences are still not conclusive whether the top red soil and the gravel deposit are derived from the same origin and of the same age (Ho, 1975; Lin, 1957).

As mentioned above, the gravel strata are Quaternary terrace deposits. The particle size of these deposits vary from a few millimeters up to tens of centimeters in diameter. Lithic sandstone and quartzitic sandstone are the main components of the gravels. Other rock types found in the gravel strata are quartzite, andesite, and occasionally hard shale and slate. Filler materials are usually composed of sand, silt and clay mixtures. The main mineralogical component of the filler material is quartz. In the -2μ fraction, quartz occupies about 40%, the rest are halloysite,

illite and kaolinite.

PARTICLE ARRANGEMENT AND STRUCTURE

In order to understand the particle arrangement and structure of gravel deposits, three sites were selected for study, i.e. Tatushan in Taichung County (Location A), Houyenshan in Miaoli County (Location B), and the Linkou Terrace in Taipei County (Location C). Their locations are shown on Fig. 2. The following paragraphs briefly report the methods of investigation and results obtained.

Particle Size Analysis — At each site, an area of 1 m x 1 m was selected and a pit 30 cm deep was excavated. The excavated material was sieved through 2 in. (5.08 cm) size and U.S. No. 4 size sieves in the field. That portion passing through No. 4 sieve was taken to the laboratory for further sieving and analysis. The particle size distribution of the coarse fraction of the samples from the three sites are summarized in Table 1. Samples from Location A and B are mainly composed of large size particles with over 70% larger than 2 in. (5.08 cm), and only about 10% fillers.

Table 1 Particle Size Distribution of Gravel Samples

Location	Sample No.	% Passing	
		2 In.	No. 4 Sieve
A	1 - 1	23.5	8.9
A	1 - 2	24.9	9.3
A	1 - 3 - A	30.1	10.9
A	1 - 3 - B	29.5	12.9
A	1 - 4	27.2	9.6
B	2 - 1	28.7	10.1
B	2 - 2	23.6	10.1
C	3 - 1	27.6	15.1
C	3 - 2	41.3	21.0
C	3 - 3	57.1	18.5

Particle Orientation — On a selected slope surface at each site, an area of 1 m x 1 m was identified and cleared of loose materials. At least 20 pieces of gravel in the intact deposit were selected and numbered. A clinometer was used to measure the bearing and plunge of the major axes of each gravel particle. The results were then plotted on a stereonet. From the equal density contours, the preferred particle orientation was evaluated. Figure 3 shows that the gravel deposits at Tatushan (Location A) and Linkou (Location C) have definite preferred orientations. Gravels at these two sites maintained their orientations of the time of deposit, even after subsequent upheaval of the land to the present terraces. The present orientations of the particles appear to be in the same directions as that of the present day river flow. The gravels at Site B, Houyenshan, however, did not show any preferred orientation, probably due to the fact that the deposits at that site are secondary deposits. Furthermore, the gravel particles at this site appear to be quite broken, possibly due to tectonic movement after deposition.

Particle Shape — To determine the ellipticity and sphericity of gravel particles, the lengths of the major, intermediate and minor axes of each gravel particle larger than 2 in. (5.08 cm) size at the three selected locations were measured. They were identified as a, b, and c respectively. From the axial ratios b/a and c/b , the gravels can be classified according to Zingg's Shape classification (KRUMBEIN, 1941) and their ellipticity and sphericity were determined according to WANG, (1969).

As shown in Fig. 4, the gravel particles at all three sites belong to the category of spherical disk shape, according to Zingg's Shape classification. The particle shape apparently reflects the effect of the structure of the parent rock, such as bedding planes and joints of sandstones, cleavages of hard shales and slates. The rocks broke open along weak planes and gradually developed into elliptical shape in the river bed by abrasion and other weathering processes. The ellipticity distribution among the gravel particles is quite uniform with an average value between 0 and -0.07 and the sphericity varies between 0.72 and 0.74.

GEOTECHNICAL ENGINEERING PROBLEMS OF THE GRAVEL DEPOSITS

Characteristics of gravel deposits are considerable different from those of clays and sands. In engineering analysis, clays and sands can often be assumed as relatively homogeneous and sometimes even isotropic. On the other hand, gravel deposits are conglomerates of very large particles and small grained filler materials and their properties can not be determined by using conventional soil testing methods. It is therefore difficult to evaluate the engineering characteristics of this type of soil. This section discusses some of the commonly encountered problems in the investigation of gravel deposits.

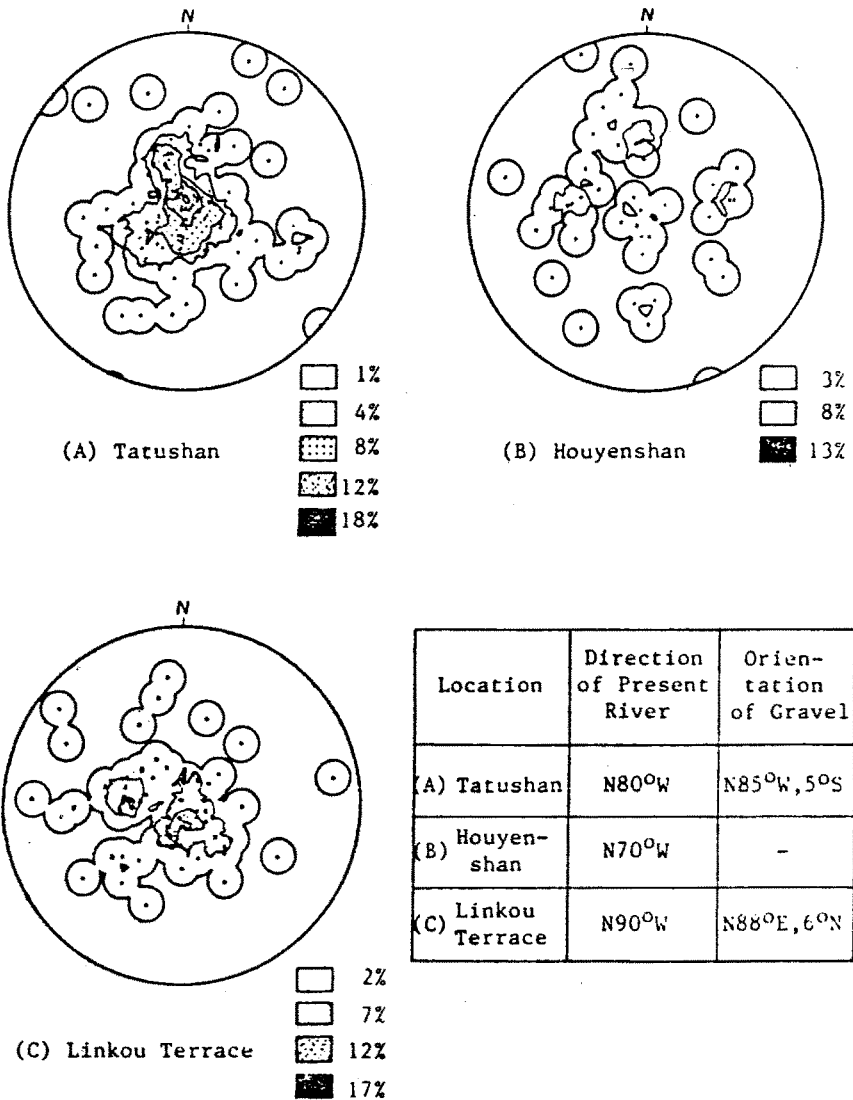
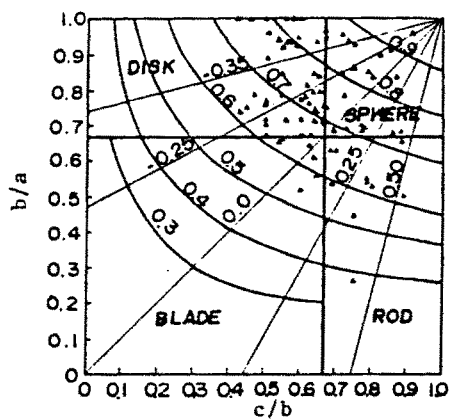
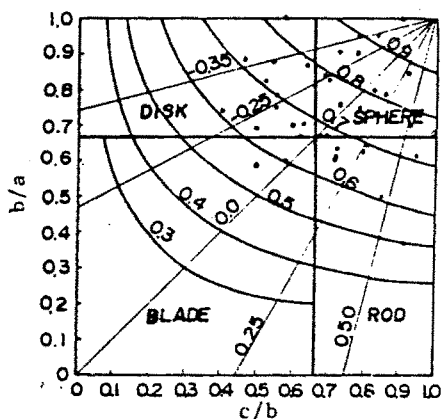


Fig. 3 Preferred Orientation of Gravel at (A) Tatushan, (B) Houyenshan, and (C) Linkou Terrace



(A) Tatushan



(B) Houyenshan



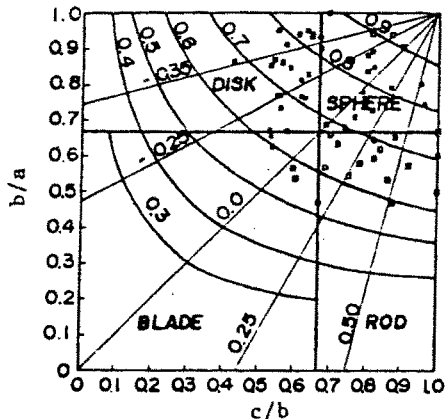
Ellipticity



Sphericity



Zingg's Shape



(C) Linkou Terrace

Location	Shape Classification	Ellipticity	Sphericity
Tatushan	Disk 55%	-0.07	0.72
	Sphere 30%		
	Rod 10%		
	Blade 5%		
Houyenshan	Disk 33%	0.00	0.73
	Sphere 37%		
	Rod 25%		
	Blade 5%		
Linkou Terrace	Disk 40%	-0.03	0.74
	Sphere 25%		
	Rod 25%		
	Blade 10%		

Fig. 4 Zingg's Shape Classification for Gravels at (A) Tatushan, (B) Houyenshan, and (C) Linkou Terrace

Site Investigation Methods — Up to the present time, several methods have been used in Taiwan for investigating sites with gravel deposits. Selection of the method or methods to be used is based on consideration of numerous factors including composition, density and depth of the deposit, and type of information required.

(1) Boring — In relatively loose deposits of sandy soils containing small granular particles, wash boring is often used. During the boring process, the fine soil particles are brought out by the washing process, but the small gravels are usually pushed to the sides of the borehole. Standard Penetration Tests are carried out in this type of stratum to obtain the relative denseness of the deposit. However, when the deposit contains pebbles and/or other larger size particles, the Standard Penetration Tests would tend to give N values which are higher than the actual values. This is caused by the effect of impact of the shoe of the split spoon on the large gravels which could not be pushed aside into the surrounding soils.

Difficulty of using washing boring increases as the size of the gravel particles and the density of the deposit increase. For boulders and large cobbles, it is possible to penetrate them by rotary drilling or coring. However, gravel deposits are usually composed of particles of sandstone, quartzite and andesite, abrasion loss of diamond bits in this type of material could be considerable. Furthermore, the roundness of gravels or pebbles tends to make the particles rotating around the drilling bits, which would make penetration most difficult and sometimes even impossible.

(2) Test Pits — By using either manual methods or backhoes, test pits can be excavated in gravel deposits. This method will offer the opportunity of direct observation of the composition, particle size distribution, orientation, structure and denseness of the deposit. In situ tests can be carried out in the pit. Two types of test pits are used.

(a) Vertical Shaft — Vertical shafts of 5 ft. (1.5 m) diameter are often dug by manual labor. The excavated materials are removed with a simple bucket, tripod and pulley system. In the gravel deposits in Taiwan, this type of vertical pits can reach a depth of 50 ft. (15 m), without any lateral bracing for a period of about one week in fine weather conditions. During the digging process, descriptions of the geological profile and photographs are taken. In addition, in situ density and moisture content tests are carried out on large size samples at every 5 ft. (1.5 m) interval. This method of investigation is usually more economical and convenient than the normal drilling method.

(b) Open Test Pit — Large size open test pits can be dug or excavated by using backhoes or excavators. This method is normally applicable to excavations in gravel strata less than 6 m in depth. The side slopes of the open cut can be made in two steps with a flat berm in between. In addition to the visual examinations and physical properties tests usually carried out, in situ plate bearing tests or in situ large size direct shear tests can be performed at desired depths.

(3) Well Exploration — This method utilizes the well digging technique which is commonly used for digging water supply or pumping wells in granular aquifers for exploration. The size of the well is usually about 12 in. (30 cm) in diameter. This method has been used to explore gravel strata to a depth of 430 ft (130 m). However, very dense strata is difficult to penetrate by using the normal well digging technique. The principle of this method is fairly simple. The gravel particles are crushed into small pieces by dropping a heavy weight into the well and the crushed stones are then removed by grabs. In most cases, only the top few meters of the well are lined with casing, and the digging can proceed without any need for further lining. Information which can be obtained from this type of exploration are obviously limited. Usually only the relative denseness and thickness of the gravel strata can be determined.

(4) Outcrop Sampling — In the northwestern part of Taiwan, many terrace deposits have been excavated and used as borrow material for roadway construction. These areas are then frequently developed for housing construction. Many of these exposed outcrops on steep slopes are available for examination and sampling.

(5) Geophysical Method — Seismic refraction and electrical resistivity are the two more commonly used geophysical methods for site exploration in Taiwan. For example, in the investigation of a tank farm in Taoyuan area, a dropping hammer was used to generate the energy for seismic refraction measurement. It was possible to explore variations of wave velocities in gravel layers up to about 100 ft (30m) in depth. At this particular site, the average seismic wave velocity in gravel deposits is about 2 to 3 km/sec (MRSO, 1978).

Electrical resistivity method is commonly used for exploring groundwater resources. From the variations of the coefficients of apparent resistivity at different depths, it is possible to interpret variations of the geological profiles.

For seismic exploration, due to the high absorption capacity of gravel layers, the energy generated by the impact dropping weights is limited and can only be used to explore shallow depths. Use of explosives for generating high energy is difficult for most projects due to government restrictions on their usage. On the other hand, electrical resistivity method does not have this problem, and its usage is gaining more popularity in this country.

Groundwater Conditions — In most gravelly terrace deposits, there is no groundwater within reasonable depth. In the central part of Taiwan, near Shanyi, no aquifer was found to a depth of approximately 330 ft. (100 m). However, perched groundwater often exists in the surface red soil layer overlying the gravels. Figure 5 illustrates a typical distribution of piezometric pressure of perched water with depth. Due to the relatively low permeability of the surface soil, the piezometric pressure increases with depth near the surface. The pressure, however, starts to drop as the water level approaches the gravel layer due to the high

Piezometric Pressure, m

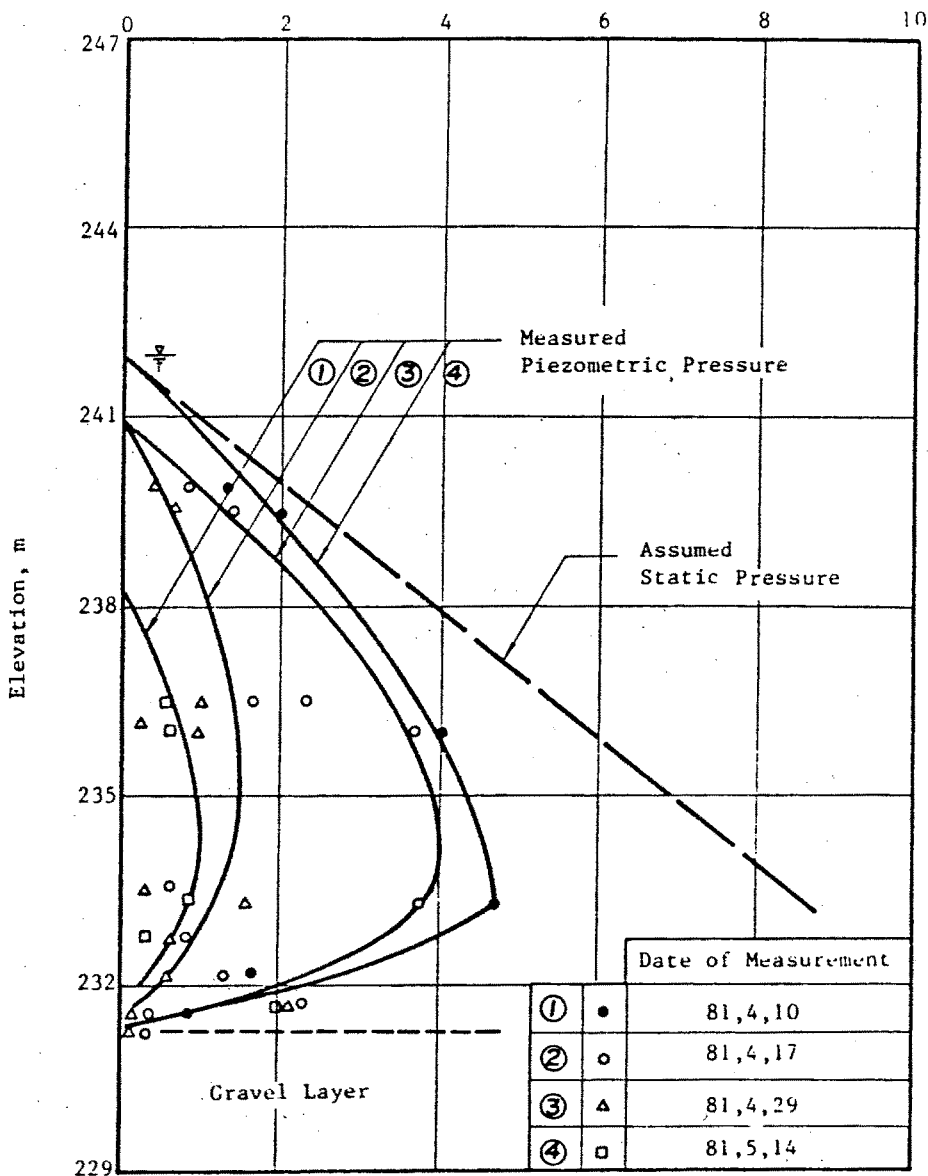


Fig. 5 Records of Piezometric Pressure in Surface Red Soil

permeability of the lower stratum. The piezometric pressures shown in Fig. 5 were measured during a relatively dry season. It can be seen that the pressures dropped with time due to dryness. However, the perched water pressures rise quickly after rain.

These unusual phenomena were often overlooked by engineers and therefore caused unexpected distress in construction. A gymnasium in Linkou area, consisting of two stories above ground and one basement level, was built on a typical terrace deposit. The subsoil consists of 3 to 7 m of red surface soil overlying a dense gravel stratum. Both the basement slab-tiebeam and spread footings supporting the building are founded in the red soil. During the initial site investigation, groundwater was not found in the majority of the boreholes. Furthermore, it was observed that the excavation surfaces during construction of the basement and footings were fairly dry, and only a very small amount of water was observed at the southeast corner of the site. Both the design engineer and the field engineer assumed that there was no groundwater underlying the site. Shortly after completion of the construction, there was continuous rainfall for several days. Large water stains were observed on the basement walls, the basement floor developed cracks and was covered with seepage water. This phenomenon became more serious after several prolonged rains. A soil investigation was then carried out at the site. It was found that the perched water in the red surface soil layer developed high piezometric pressure in the excavated area and created an uplifting pressure on the basement floor. In the original basement design, the effect of uplift was not taken into account. After realizing the existence of the perched water, the basement slab was redesigned and reconstructed as a structural slab. Thereafter, no further distress or leakage of water was observed.

Stability of Slopes in Gravel Deposits — One of the very special characteristics of gravel deposits in Taiwan is their steep side slopes. The slopes can be divided into two broad categories, each with its own characteristics. They are natural slopes and man-made cut slopes. Figure 6 shows the measured records of slope heights and slope angles of gravel deposits in two localities. It is interesting to note that most of the natural slopes have gradients less than 40° and the height varies from 33 ft. (10 m) up to 660 ft. (200 m). On the other hand, many man-made cut slopes have much steeper slopes, some even up to $80^\circ - 90^\circ$. Several of the near vertical slopes are stable even at a height of about 200 ft. (60 m). These steep cut slopes are often seen along the sides of highways, sloopeland developments and borrow areas.

The stability of natural slopes, therefore, their heights and gradients, are obviously related to many factors such as topography, precipitation, weather, age and depositional environment, etc. However, many man-made slopes are found to be stable with near vertical faces, and in many cases even without surface protection. It is apparent that the mechanisms responsible for slope stability of gravel deposits are different from those for ordinary soil slopes. The following paragraphs attempt to discuss these factors.

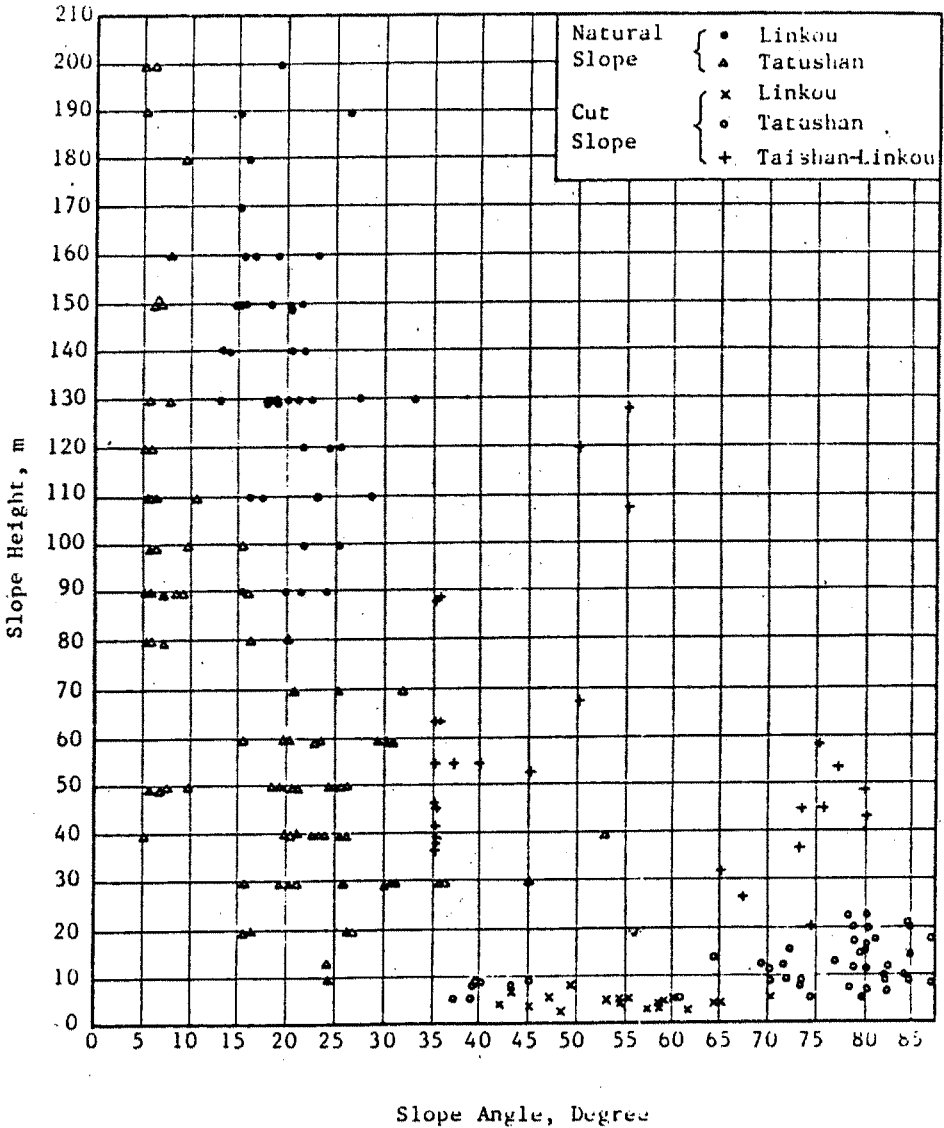


Fig. 6 Slope Height Versus Slope Angle for the Slopes of Gravel Deposits in Northwestern Taiwan

(1) Strength Properties of Fine-Grained Filler Material — The content of fine-grained filler material in most of the gravel deposits in Taiwan is about 25% by weight. The filler materials usually occupy the voids between and tend to envelop the gravel particles. The amount of direct particle-to-particle contacts between the gravels are therefore rather small. If a slope failure is due to shearing of the filler material, the stability of a slope is then governed by the strength characteristics of the fillers. Due to the small amount of filler material present in the gravel deposits, it is often difficult to obtain undisturbed samples either by sample tubes or hand-dug blocks of the fine-grained filler material. Therefore, commonly used testing methods for determining shear strength of soils cannot be used. Figure 7 illustrates the strength properties of the filler materials in the Linkou Gravel deposits. Part of the data was obtained by using hand penetrometers and the others were interpreted from results of unconfined compression tests on samples taken from the surface red soil layer. The figure shows that strength of the clayey filler material varies considerably from very soft to hard. However, fairly definite trend can be seen between the strength and the water content. Generally speaking, those materials near the slope surface have lower strength due to weathering effect. On the average, the unconfined compressive strength of the filler material varies from 2 kg/cm² to 3 kg/cm², natural water content is between 15% and 25%, and the angle of shearing resistance in terms of total stress is about 25°. By using these properties, the limiting height of a vertical slope is about 76 ft. (23 m) according to the conventional method for slope stability analysis (such as HOEK and BRAY, 1977). However, actual observations indicate that many steep slopes are stable at much higher height. Obviously, there must be other factors which also contribute to the stability of these slopes.

(2) Interlocking of Gravel Particles — It was described in a previous paragraph that the gravel particles in most of the gravel deposits exist in regular arrangement and the particles are flat in shape. When the flat gravel particles are arranged with its major axis in a horizontal direction, the particles attain their highest stability. The regular arrangement of flat shaped particles appears to be similar to a brick wall. Due to the very hard nature of gravel particles, potential sliding surfaces seldom cut across the particles but develop in a zigzag form as illustrated in Fig. 8.

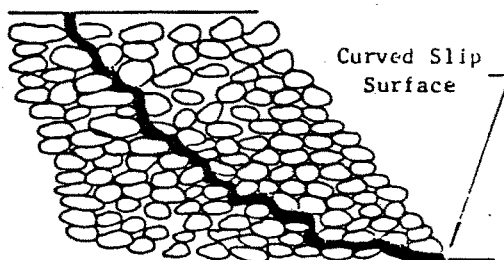


Fig. 8 Slip Surface in Gravel Deposits

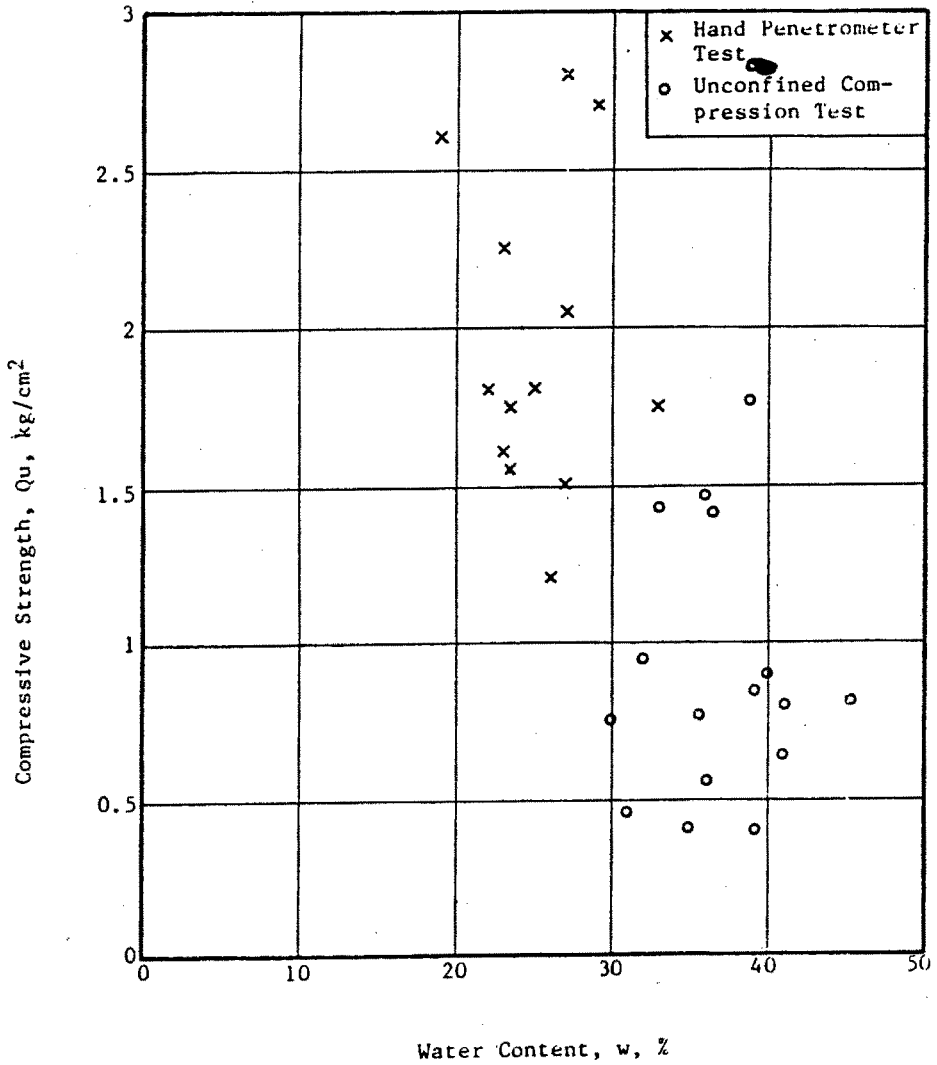


Fig. 7 Strength of Fine-Grained Filler
Material of Gravel Deposit at Linkou

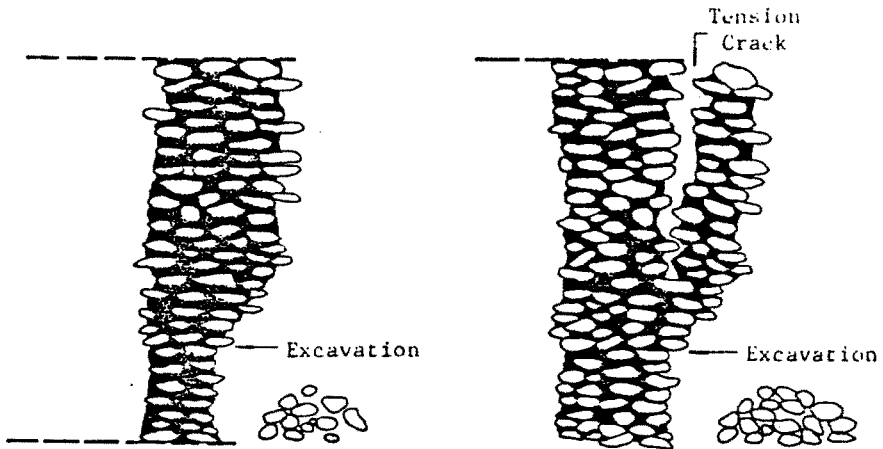


Fig. 9. Toppling Failure due to Excavation at Toe of a Slope

Fig. 10(a). The coefficient of subgrade reaction k can be calculated from the slope of the load-settlement curve. Table 2 lists the k values obtained from several different sites. The k value of this type of gravel deposit is quite high, more than 10 kg/cm^3 .

(2) Type 2 — For gravel deposits with partial particle contacts, the load-settlement curves, as obtained from plate loading tests, appear to be in reverse curvature. At the beginning under small load, the slope of the curve is large and it gradually decreases as the loading is increased, see Fig. 10(b). This phenomenon can be explained as follows. At the beginning of the test, there are few particle-to particle contacts between gravel particle and the major part of the loading is taken by the filler material. As the loading increases and the amount of settlement reached a certain degree, and the amount of voids has reduced significantly, the number of particle contacts increases. As a result, the bearing resistance increases.

(3) Type 3 — For gravel deposits with no apparent particle-to-particle contacts, the bearing resistance is solely dependent upon the strength characteristics of the fine-grained fill material. The load-settlement curve obtained from test on this type of deposit resembles that of fine-grained soils as shown in Fig. 10(c). The bearing capacity of this type of gravel deposit is thus much lower than the other two types.

If the flat gravel particles are arranged with their major axis in a more or less horizontal direction as shown in Fig. 8, a slipping block cannot slide unless the gravel particles along the shearing surface rotate their axes to a direction parallel to the sliding surface. Since the regular arrangement of gravels gives a well interlocking between the particles, rotating a particle will generally require a large force. This resisting force is believed to be the major contributor to the stability of a gravel slope. The interlocking effect of gravels can be easily observed from the overhanging of many gravel particles at cut slope surfaces.

It should be pointed out that the particle-to-particle friction between gravels may not be a dominant factor for control of slope stability, because firstly there are only few direct contact points between gravel particles, and secondly the relatively smooth particle surfaces of the gravels can only induce low frictional resistance. The values of the angle of internal friction as determined from sliding test between two gravel particles are in the range of 25° to 30° . It is therefore quite obvious that it is not the low frictional angle of gravels but is the strongly woven interlocking particle arrangement responsible for the stability of a near-vertical slope.

Further proofs of the importance of particle interlocking in gravel deposits are demonstrated by the toppling action of excavated faces. Gravels in the terrace deposits are often being used as sources for crushed stone borrow material. The usual method of excavating these gravel borrows involves the use of a backhoe to excavate the material at the toe of a deposit. When the digging reaches a certain depth, vertical cracks develop at the top of the slope as illustrated in Fig. 9. These cracks gradually extend downward and sidewise, and finally toppling failure of the slope occurs. The failure surfaces are usually very steep and the toppling occurs in thin slices. Due to this type of failure mode, many near vertical man-made cut slopes exist.

At present, no rational solution of stability analysis can be applied to the gravel deposit slopes. Many engineers recognize the fact that these cut slopes can be fairly stable for a relatively short period of time. However, for long term stability, the slopes surface must be protected against erosion and weathering.

Bearing Capacity and Settlement of Gravel Deposits — In Taiwan, in situ plate bearing tests are often used to determine the bearing capacity of gravel deposits. Depending upon the groundwater conditions, the tests are either performed in an unsoaked or soaked condition. According to the structure of gravel deposits, the load-settlement curves of plate loading tests can be divided into three types:

(1) Type 1 — For gravel deposits with very dense structure and close particle contacts, the bearing capacity is usually very high. Within the normal range of loadings applied to a plate loading test, the settlement is quite small and the load-settlement curve appears to have a linear relationship with no apparent failure point as illustrated in

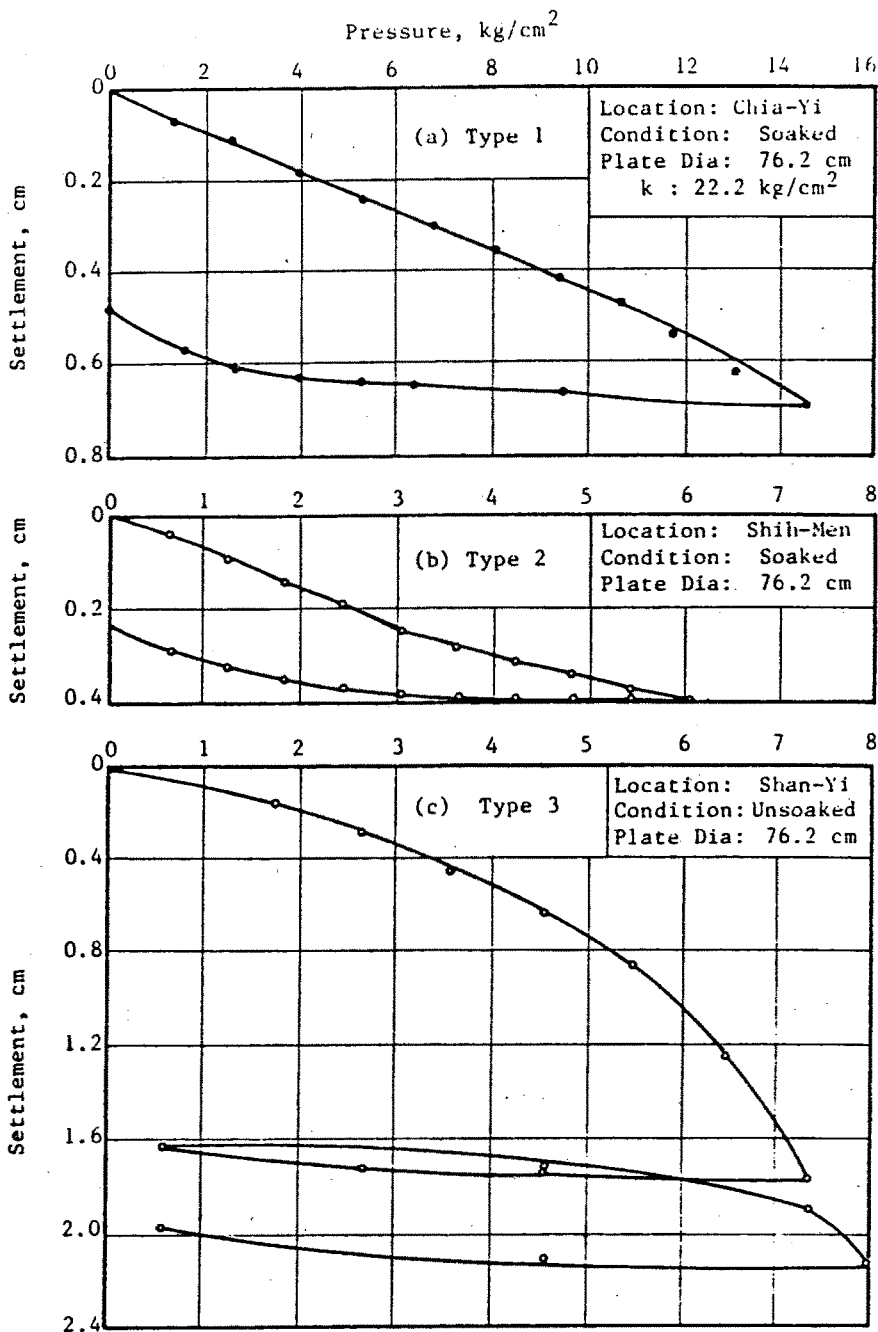


Fig. 10 Load-Settlement Curves of Gravel Deposits

Table 2 Results of Plate Loading Tests

Location	Coef. of Subgrade Reaction, kg/cm ³	Plate Diameter, cm	Test Condition	Max. Applied Pressure, kg/cm ²
Linkou	13.8	76.2	Unsoaked	4.4
	13.8	76.2	Soaked	5.2
Shih-Men	37.0	76.2	Soaked	6.1
Chia-Yi	22.2	76.2	Soaked	14.6
	14.3	76.2	Soaked	14.6
Chung-Li	33.0	30.5	Unsoaked	5.2
	64.0	30.5	Unsoaked	5.0
Tao-Yuen	26.7	76.2	Unsoaked	7.5

SUMMARY AND CONCLUSIONS

Gravel deposits are commonly found in the central western part of Taiwan. Many highways and roadways cut through this type of deposit. Due to rapid economic development in the country, development of hilly regions involving terrace gravel deposits becomes more important.

The majority of the gravel deposits in Taiwan are composed of a matrix of large size gravels with their voids infilled with reddish colored soils. Stability analysis of these deposits, either on the basis of the shear strength of the gravel conglomerates or the strength parameters of the fine-grained infill materials, would not give satisfactory explanation of many slopes in the region, especially, many cuts with near vertical slopes appeared to be safe even after sustained rainfall. This paper presents a study on the geology, structure, physical and compositional characteristics of this type of deposit in an attempt to elucidate the mechanisms responsible for its stability and other related engineering problems. Discussions were also presented on methods of site investigation in this type of deposit. The main conclusions which can be drawn from this study are:

- (1) The choice of a most suitable method for site investigation of gravel deposits should depend upon the size of project and area involved. For a small project with a compact site, pit excavation may be sufficient. Geophysical method together with few open pits can be used for larger project sites.
- (2) Perched groundwater often exists in the surface red soil layer overlying the gravels. The existence of the perched groundwater should not be overlooked in design of structures especially structures with basement.

- (3) Results of study of particle arrangement and structure show that many gravel deposits have regular arrangement. The interlocking between and alignment of the gravel particles appear to be the main mechanism responsible for the stability of many gravel slopes. However, at present, there is no rational method of analysis available for analyzing this type of slope.
- (4) Plate bearing test is a useful and convenient method for evaluating the bearing capacity and settlement of gravel deposits. Except for tests performed on the top red soil, the bearing capacity of gravel deposits is generally high with limited settlement.

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