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Geotechnical Failures Case Histories of Construction on Soft Soils, Forensic Investigations and Counter Measures in Indonesia

Paulus P. Rahardjo[1]

[1]Parahyangan Catholic University, Jl. Ciumbuleuit No. 94 Bandung , INDONESIA

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Abstract: Geotechnical failures of construction on soft soils frequently occur in many locations in Indonesia and several of them have been due to negligence or lack of knowledge in appropriate technology. This paper discusses geotechnical forensic investigation of some case histories and technology involved for corrective measures that are generally practiced in Indonesia and also discusses some aspects of the analytical and empirical methods of geotechnical analysis. Particular focus is placed on the case histories of failures of excavation and embankment on soft soils. Some cases have uncommon causes and become new lessons to consider in design and procedure of construction. In most cases, the paper is based on the author's experience in the last two decades. Although this paper does not explain all types of the geotechnical failures occurrence in Indonesia, the scope of the paper highlight similar events commonly found.

Keywords: geotechnical failures, forensic geotechnical investigation.

1. Introduction

Geotechnical failures of construction on soft soils in Indonesia have occurred in many different ways. These problems have been faced throughout the country. Most of the failures occurred due to negligence, lack of knowledge and lack of data. In some cases the failures have killed many lives and damages many infrastructures.

According to Rahardjo [19], these cases are coincident with the existence of easily degradable materials, highly water sensitive soils or soils in underconsolidation state or material loosely bound such as colluvium and recent sediment. The cases are rarely reported due to reluctance or fear of loosing business of the owner, the contractors or the consultants, most of them are seldom reported or exposed to public so that many of them are kept unknown, hence the problems are being repeated in similar situations. The real statistics of geotechnical failures occurrence are a lot more than are reported.

Based on the experience of the author, it may be concluded that many engineers are not aware of the generation of excess pore pressure that are developed in soft ground when loaded. In some situation, the engineers design blindly following text book without understanding which situation is appropriate for his cases compared to textbook which are generally theoretical. A good text book should discuss examples of the real situation for each theory.

Soft soils can be naturally made and also as a man made product such as tailing materials. Some serious mistakes were caused by unwillingness to cover the cost of safety. An example of landslide disaster occurred in the tailing materials resulted from the gold mining at Cisoka, Banten. More than 120 people were killed in these slides in some areas including Desa Lebak Situ, Lebak Gedong, and Lebak Sangka (Pikiran Rakyat, 2001). Fig.1 and Fig. 2 show people looking for their family members in the debris. Tailing dams were regarded costly and in some cases are omitted. Since the tailing material can flow, sliding cannot be avoided even under gentle slope.

Fig. 1 The slide at Lebak that killed about 120 peoples (after Harian Pikiran Rakyat, February 12, 2001).

Prior to the landslides debris flow, the rain intensity was very high. It was predicted that the rain water penetrate into the tailing materials and dykes and causing high water content that result in changes of the soil state into liquid.

Many dykes and embankment failed which are mostly due to placement of an uncontrolled material or non-engineered fill over soft ground. In many cases, these failures are not properly designed nor inspected during

*Corresponding author: rahardjo.paulus@gmail.com

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design as well as during the placement of the fill. In other cases, excavation and cut slopes that failed are due to the lack of information on foundation soil stratification and their engineering characteristics.

Fig. 2 People of Kampung Kosala - Banten looking for their family members after the slide (after Harian Pikiran Rakyat, February 11, 2001).

2. The Origin and Existence of Soft Soils in Indonesia

It is commonly understood that soft soils are defined to have shear strength of 12.5-25.0 kN/m^2 or very soft when the undrained shear strength is less than 12.5 kPa. Organics and peats are also classified into soft soils. These materials are classified into clay soils when the organic content is less than 25%, organic soils with 25 – 75 % organic content and peats when organic content is higher than 75%.

The soft sediments were deposited in ‘recent age’ which is geologically less than 10.000 years or holocene in the quarternary period (in the geological map, these soils are known as Qa).

Fig. 3 shows the distribution of soft soils in Indonesia. They are deposited abundantly at east Sumatera, North Java, South Kalimantan and almost along big rivers such as Mahakam river in East Kalimantan.

Most soft soil deposits are also in the estuary area or delta. The largest delta deposit most well-known in Indonesia is the Mahakam Delta, located in East Kalimantan near Samarinda (Fig. 4). A lot of data have been collected in this delta [20].

3. Typical Soft Soils Characteristics

Soft soils can be identified using laboratory testings as well as in situ testings. Common methods of insitu testings are the use of Vane Shear Test (VST) which is a rather direct method of measuring shear strength of cohesive soils and Cone Penetration Test (CPT) where the soft soils can be determined as the tip resistance of the soils, qc, is less than 60 kPa or about 6 bars. The use of Standard Penetration Test (SPT) is not recommended for most sensitive soils have N_{SPT} less than 4, most of them practically 0.

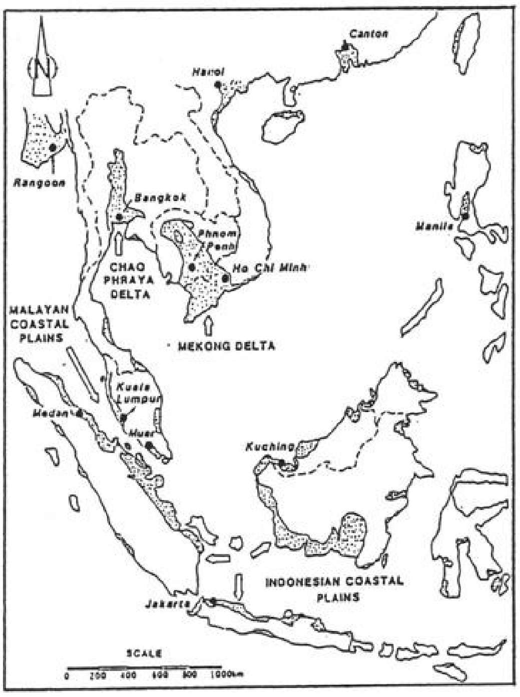

Fig. 3 Distribution of soft soils in Indonesia [5].

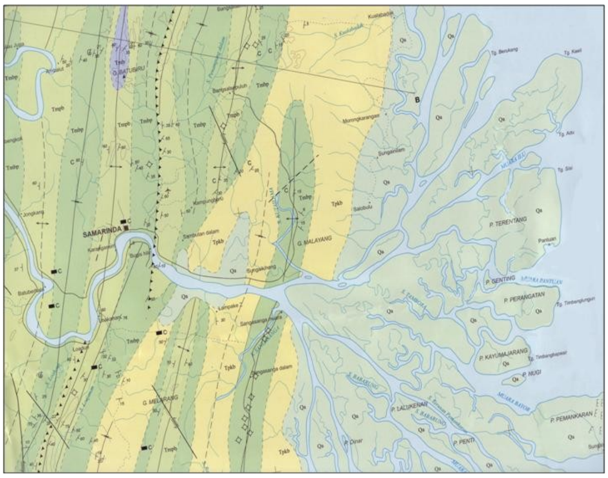

Fig. 4 Largest well known Mahakam Delta at East Borneo [8].

The use of CPTu and VST are the most common in situ testings as illustrated in Fig. 5 and Fig. 6 as follows. This particular examples were taken at the Mahakam Delta for SPU project owned by PT Total Indonesie across Nubi island.

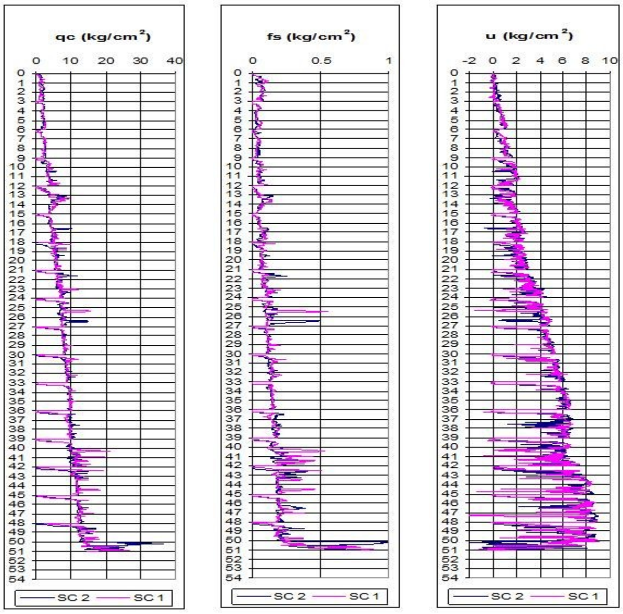

Fig. 5 Result of CPTu in soft Mahakam clay [20].

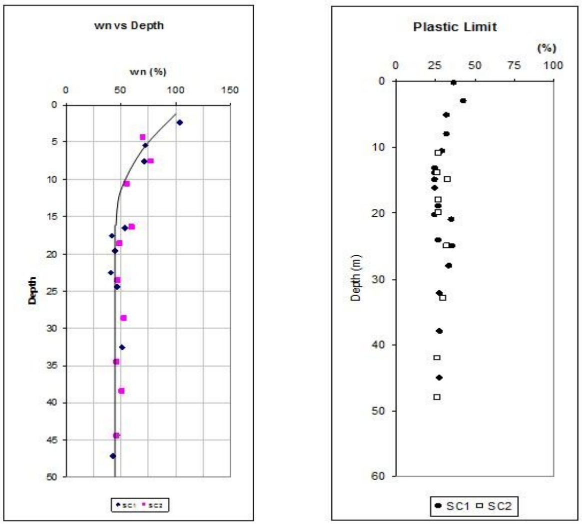

Fig. 6 Typical soil data on soft Mahakam Clay [20].

The results of the plot show that the characteristics of soft delta Mahakam river is consistent (Fig. 7). The data plot show the natural water content is closed to liquid limit of the soils, which is understood that the soil behavior is very close to its liquid limit state. The data plots of the compression index in the upper layer are about 0.8.

4. Case Histories of Construction on Soft Soils

It is important and illustrative to discuss about case histories, especially in Geotechnical failures. This paper presents a number of interesting geotechnical failures, discuss the geotechnical forensic investigation and provide the method of counter measures. The cases may be divided into :

i. Embankment and Reclamation on soft soils
ii. Failures of Excavations in soft soils
iii. Softening materials in contact with water including dispersive and expansive soils
iv. Embankment Failures due to Soil Dispersions
v. Failures of uncontrolled fill embankment
vi. Failures of Embankment of Sandy Soils due to Seepage Problems
vii. Failures of Bridge Abutment on soft soils
viii. Liquefying soils under seismic loading
ix. Failures of Earth Reinforced Embankment

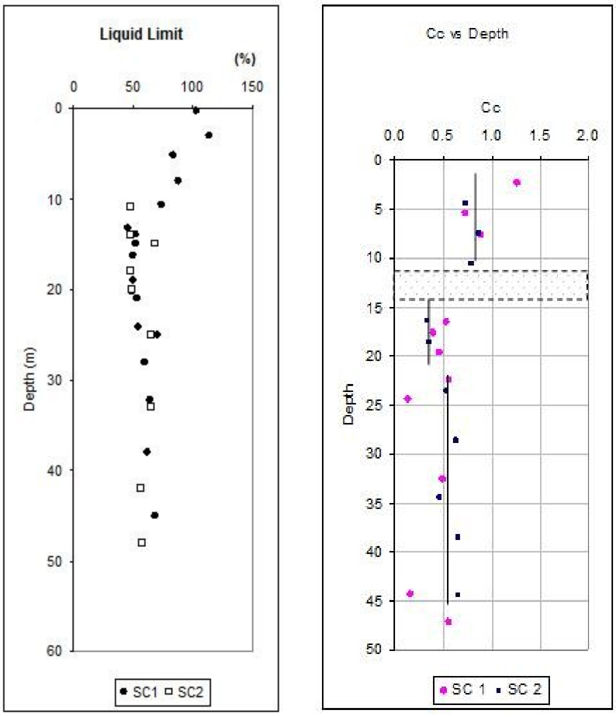

Fig. 7 The plot of water content and compression index [20].

5. Embankment and Reclamation on Soft Soils

5.1 Successful and Controlled Reclamation Work

The classical issues in reclamation works on soft soils are the stability of the soft layer which has limited bearing capacity and large long term settlement. As such, the common geotechnical practice is solving the problem by the use of vertical drains (PVD) and staging the fill placement (Fig. 8). Basically, the staging is based on limit of allowable excess pore pressure which control the stability of the system. The vertical drains help to speed up the dissipation of the excess pore pressure.

Fig. 8 Installation of the Vertical Drain (PVD) (photographic documentation, Rahardjo).

A good example of the practice is an SPU project in East Kalimantan where the owner is to construct a procession unit. The site condition prior to reclamation is shown on Fig. 9.

Fig. 9 Initial condition of the project site [20].

The next important part of the work is to prepare the geotextile to cover the original ground. The purpose of the geotextile at this stage is to separate the natural soil grade with the fill material (generally sand). Fig. 10 shows the technique.

Fig. 10 The use of geotextile for separation between foundation soils and the backfill material

5.2 Failures of Embankment on Soft Soils

Many slope failures in Indonesia have been due to the construction of embankment on soft soils. The existence of soft soils is very wide and most of them are the location of big cities or important development.

The main reason is the bearing capacity failures of the foundation soils, however in most part of the country, the incidence are generally due to the increase of excess pore water during loading. Most contractors in Indonesia are not aware of these phenomena. Typical example of this type of failure is in the development located north of Samarinda along Mahakam River.

In this particular landslide, deep soft soil exists under the development. The fill material was imported from other borrow area and was to be constructed 17 m high. The contractor fully compact the fill during placement, however no geotechnical design was involved. Sliding took place when the fill reached 15 m high. The slide was a typical deep seated failure.

Fig. 8 Failures of fill constructed on soft soil foundation in Mahakam River, East Kalimantan (photographic documentation, Rahardjo).

Another important aspect of this slide is because there is significantly different stiffness of the embankment soil and the foundation soil as described in Fig. 12. Since the embankment soil is much stiffer, cracks were developed upon sufficient movement of the foundation soil. This movement was started mainly in the slope and then extending to the upper area. Remedial measures were carried out by re-grading, changing elevation, and leaving the construction until sufficient excess pore water pressure was dissipated.

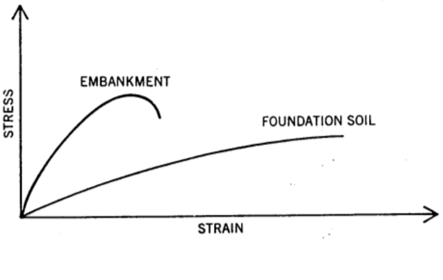

Fig. 9 Different stiffness of foundation soil and fill material.

6. Failures of Excavation in Soft Soils

Deep cuts are frequent features in urban areas mainly for the basement. The design of cut slopes or excavation is influenced by the purposes of the cut, geological conditions, in situ material properties, seepage pressures, construction methods and the potential occurrence of precipitation, erosion and earthquakes. In some situations, cut slope stability at the end of construction may be critical design consideration. Conversely, cut slopes, although stable in the short term, can fail many years later without much warning.

In contrast to embankment slopes, the pore pressure within the cut in clays increases over time. This increase is accompanied by a swelling of the clay, which results in reduced shear strength. Thus the factor of safety decreases over time until an unstable condition is reached. This explains why clayey cut slopes along the way from Cianjur to Jakarta (as may be seen many of such occurrences shown in Puncak, West Java) frequently fall a long time after initial excavation. A number of corrective measures are being done such as protecting the exposures from contact with water and climate conditions (Fig. 13).

Fig. 10 Protection of the cut slope from severe weathering located at Citatah, West Java (photographic documentation, Rahardjo).

For cuts in overconsolidated clays, the in situ shear strength is a direct function of the maximum past pressure or may be termed yield pressure. However, if the clay is subjected to long term unloading conditions (permanent cuts), the strength of the clay no longer depends on the prior loading. The loss in strength has been observed to be a time dependent function related to the rate of dissipation of negative pore pressure. In practice, the loss in strength after cuts are made is not easily determined.

In most areas in West Java, a lot of areas (such as in Padalarang, Plered, Cikampek, Cikarang, Karawang and most part of Bukit Indah City) are well known as expansive clays. When the soil is in its original condition under the natural water content, it shows high shear strength. Steep cut slopes can be constructed in this area and most of them initially stand firmly. But after a certain time, they started to fail.

An event of failure in cut slopes occurred in excavation for basement in Surabaya. This excavation was conducted in soft soil protected by sheet piles with a depth cut of 8.0 m. The failure was understood as a result of significant deformation of the sheet piles and failure at the toe (Fig. 14). Emergency action was to avoid water penetration through the cracks by plastic sheet cover. Further action at this event was by constructing soldier piles of 800 mm diameter at an interval of 1.50 m.

Fig. 11 Slope failures during excavation for basement in Surabaya (photographic documentation, Rahardjo)

7. Failures of Earth Retaining Structures in Soft Soils due to Excavation

Soft soils are responsible for the failures of many retaining structures. A number of such failures are because the mechanism which is not understood by the designers as well as the contractors. One of these examples is the failure of sheet pile embedded in the soft soils East of Surabaya. The depth of the soft soil layer reaches about 20 m where 12 m of a steel sheet pile were driven. The failures occurred when the excavation was about 3.0 m depth. Heaving was detected one day before the failure indicating deep sliding and the sheet pile underwent kicking out at the toe causing loosening of the strutting system and imbalance in stability. Fig. 15 and Fig. 16 explains the situation of the sliding and failures of the structure.

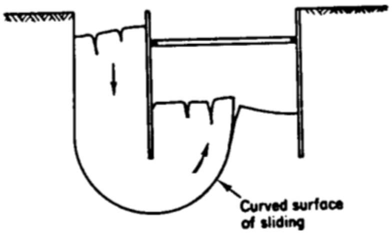

Fig. 12 Failure of sheet piles due to deep sliding of excavated soft soils [16].

Fig. 13 Failures of sheet piles in soft soils due to deep sliding underneath the structure in Surabaya (photographic documentation, Rahardjo).

8. Failures of Embankment due to Softening of Expansive Soils

Soil softening is one of the major caused of slope failures. Many types of soil and rock in Java are subjected to softening after exposure to water and climate. In many cases, these slopes shall be protected from contact with water (Fig. 17).

At Cikarang, however, the slope at a bridge abutment failed because of the contact between the expansive soil and water in the main drainage canal. Forensic geotechnical investigation lead to the conclusion that soil softening of the expansive material is in contact with the water caused the failure. The expansive soils, although well compacted, is subjected to absorption of water. This process started from the surface and result in a significant strength decrease.

A study by Rahardjo and Meilani [13] for soils in Padalarang shows that the influence of saturation has a very significant effect on the decrease of soil shear strength. Upon saturation, a natural and compacted sample in Padalarang may loose as much as 70 – 90 % of its shear strength.

Fig. 14 Failures of abutment fill due to soil softening (photograph documentation, Rahardjo).

9. Embankment Failures due to Soil Dispersions

In some cases, embankment has been constructed using dispersive soils such as silts (Fig. 18). Most of the reason is due to the availability of this material near the site and because of the limited budget to import better materials from outside the project area. One of such a case was found in the Samboja Dam, East Kalimantan. This dam was constructed in 1979 and has experience a number of failures during construction. Although the dam is very low (about 8.0 m), the stability is endangered by the erosion due to dispersion of soil in the upstream area. In 1999, a study was performed to increase the safety of the dam. The result of the study recommended that the dam should be heightened by about 3.20 m and this is done using non dispersive material.

Fig. 19 shows design rehabilitation of these slopes. To protect the dispersive material, a piece of geotextile was laid and gravelly sand was used to cover and increase the height of the dam.

Fig. 15 Embankment failures due to soil dispersions at Samboja Dam, East Kalimantan (photographic documentation, Rahardjo).

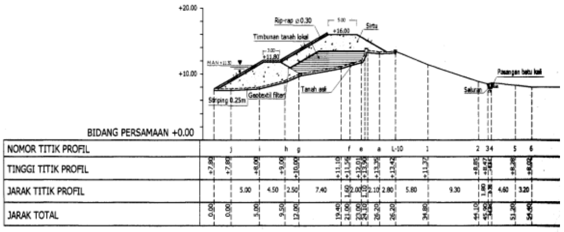

Fig. 16 Slope rehabilitation of dispersive embankment dam in East Kalimantan (after PT. Ganesha Piramida, 1999).

10. Failures of Uncontrolled Fill Embankment

Fill slopes involving compacted soils including highway and railway embankments, landfills and reclamation, earth dams and levees. The engineering properties of materials used in these structures are controlled by the quality of the material from the borrow area, method of construction and degree of compaction. In general, the parameters used for analysis are more controllable, and the slope potential sliding planes are more definable. The practice for slope analysis in Indonesia is usually conducted at the end of construction (seldom in the long term condition, except for important dams), earthquake condition and during the rapid drawdown for a dam. However, the lack in this analysis is that, during the course of the construction, the slope might experience instability due to imbalance of forces or most frequently due to the development of pore water pressure.

Many slope failures in West Java are caused by uncontrolled fill placement such as in North of Bandung and in Purwakarta. It is shown in Fig. 20, very high fill (about 25 m) was placed without clearing of the original slope and without compacting. The slope failed because of the quality of the fill and the existing soft soils under the embankment. To overcome this problem, the fill was added at the toe of the slope bridging the gap with the other hill across the embankment. Additional fill was added to flatten the slope in a more engineered way.

Fig. 17 Uncontrolled high fill embankment, Nort of Bandung (photographic documentation, Rahardjo).

Another example of landslide in poorly compacted fill was found in Purwakarta, where the fill was about 6.0 m thick placed on top of claystone. The fill moved during the 1996 wet season and continued moving until 1999. Emergency action was done by covering the sliding area with plastic sheets to prevent water infiltration into the sliding soil. Fig. 21 shows this emergency action. Forensic geotechnical investigation using CPT revealed that compaction lift was done at very high fill thickness as shown in Fig. 22. In this figure, it is shown that the compacted area shows higher tip resistance revealing the thickness of the lift, which is about 1.50 m. The softer part of the fill has higher void ratio and hence forming accumulation of water during rain.

This landslide endangered factory building on top of the slope. Action recommended at this part was by constructing rows of bored piles of 400 mm diameter and 10 m depth. Finite element analysis on this slope problem was conducted by Rahardjo (1999) as shown in Fig. 23. This method is effective and enable to stop movement of the poor fill material. In 2001, the slope was rehabilitated by a contractor, not in accordance with the geotechnical recommendation. The contractor used gabions instead of bored piles. Due to soft layer underneath the gabions, the slides are reactivated. Heaving occurred under the gabions and subsidence due to slides damages the infrastructure. An important lesson is taught by the difference in the concept since the contractor has used conventional slope stability analysis assuming the soil a rigid body, which is not true for soft soils. It has to be noted that the equilibrium condition of rigid body and deformable body shall be further studied.

Fig. 18 Emergency action for handling landslide in Purwakarta by Temporary Cover [14].

In the lower part of the sliding areas, re-grading was recommended in combination with surface drainage systems and the use of horizontal drains. The horizontal drains was drilled using conventional drilling machine sloping at 5 – 8 %.

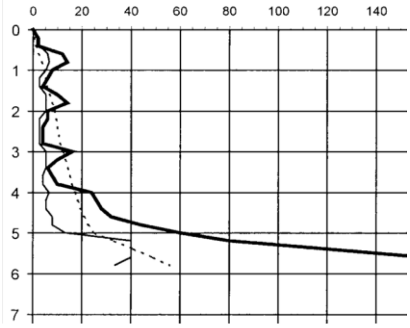

Fig. 19 Indication of compaction considerable thickness lift [14].

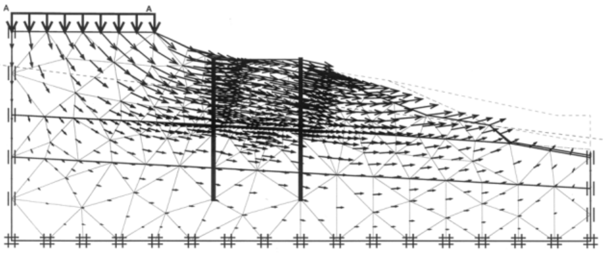

Fig. 20 Numerical modelling of landslide in Purwakarta [14].

Poorly compacted fill material has been responsible for the failure in a development area in Cipanas (Fig. 24). This area is hilly and many cuts and fill were conducted to meet the landscape for the development. The amount of fill reached more than 2 million m^3 and placement were done during rain. The fill material has very high water content. After 1 year of placement, the fill started to form many cracks, which are easily penetrable by rainwater. The slide occurred in the following rainy season. This lesson is very important that compacting under high water content has the risk of cracking and later on, water infiltration.

Fig. 21 Sliding of poorly compacted fill material in Cipanas, West Java (photographic documentation, Rahardjo).

11. Failures of Embankment of Sandy Soils due to Seepage Problems

Embankment of sandy soil, which is not protected against water penetration has resulted in 1995 failures as found in Karawang along Jakarta – Cikampek Toll Road (Fig. 25). The slope is gentle, having an inclination of H : V = 3 : 1. The slides occurred during a long run, where due to the high permeability of the sand fill material, water penetrated into the embankment and water percolation inside the body of the embankment cannot be avoided. The relatively flat position of the slope was one of the main cause to ease the water penetrate into the embankment since insufficient surface drainage was available.

Fig. 22. Failures of slopes consisting of sand fill materials (photographic documentation, Rahardjo)

The result is, internal erosion took place and the sand was eroded to the toe of the slopes. Initially small spring appeared at the toe and this spring became wider and finally causing the slides. This has initiated further failures of the embankment as shown in the figure and water has accumulated at the toe.

It was finally decided that the corrective measures for this slide was by constructing the slopes using geotextile earth reinforcement and better management of the surface water.

12. Failures of Bridge Abutment and Sheet Piles due to Excess Pore Pressure in Soft Soils Under Fill

Many bridges in Indonesia are constructed across soft layers. Many of them failed after backfill behind the embankment. These types of failures have been found to be typical in many areas due to excessive pore water pressures developed under the backfill.

The following figures (Fig. 26 and Fig 27) show the failure of bridge abutment during the backfilling behind the abutment of about 4 m. The soft soild underneath the foundation of the abutment move laterally causing excessive displacement of piles.

Fig. 23 Failures of bridge abutment [21]

Fig. 24 Lateral displacement of bridge foundation [21]

Another unexpected mechanism was the failure of a sheet pile structure in Palembang along the Musi River. The soil is found to be soft clayey silt 12.0 m thick. The corrugated concrete sheet pile was installed in the year

2000 and 3.0 m – 5.0 m fill was placed one year later. The failure is due to the excess pore pressure developed during filling (Fig. 28). This pore pressure is estimated to be about 50 – 60 ton/m' as the placement was carried out in relatively very short time. Either textbook or conventional method of calculation does not take into account this excess pore pressure, which should have been controlled by staging the fill placement.

Fig. 25 Failures of sheet piles due to excess pore pressures during fill placement in Palembang (photographic documentation, Rahardjo).

A similar situation was also due to the failure of sheet piles in Jambi, Sumatera where the failure was induced by excess pore pressure generated by the backfill (Fig. 29). In the geotechnical forensic investigation, it was found that the design did not include the magnitude of excess pore pressure nor any method proposed to dissipate the pore pressures such as installation of vertical drains or staging fill placement.

Fig. 26 Failures of sheet piles due to excess pore pressure during fill placement.

13. Foundation Failures and Lateral Spreading due to Liquefaction

One of the damages caused by earthquake to the original ground is the settlement of ground surface and lateral spreading due to liquefaction. In many cases, slope failures may result upon the excessive pore water pressure developed during the earthquake.

Sliding due to earthquake induced liquefaction is the main event causing failures as encountered at Padang Pariaman (Fig. 30) earthquake 29 September 2009 and in the coastal area of Maumere City during the 12 December 1992 earthquake in conjunction with liquefaction mechanism.

Fig. 27. Lateral displacement in Padang earthquake (photographic documentation, Rahardjo)

In Maumere City, although the slope in the coastal area is normally very gentle (about 10 – 15^o), due to high excess pore pressures, the sandy layer practically loses all of their strength causing flow liquefaction in submarine soil. Table 1 describes the typical soil condition of Maumeris predicted very loose sandy silt layer are predicted to experience liquefaction flow failures. The upper part of the sandy layer down to about 20 m has very low SPT-N values, which is very potential to liquefaction. An analytical calculation made by Rahardjo & Meilinda [18] verifies this condition. Submarine slide occurred in the coastal area where infrastructure such as road and utilities was damaged.

Explanation of liquefaction flow failures were made by Castro [4] where sloping ground induced shear stresses on the soil element below. Under normal condition, this initial shear stress is lower than the peak shear strength of the soil, and hence, the slope is stable when there is no disturbance. However, during earthquake, straining of the soil element cause decrease of shear strength to its residual or steady state condition. When the undrained steady state shear strength is lower than the initial shear stress, liquefaction flow failures take place. Fig. 33 shows the stress strain condition of this mechanism.

Another phenomena of this type of slide occurred during the Bengkulu earthquake of the year 2000 where sheet piles with silty sand backfill failed during the earthquake (Fig. 34). The failure is due to slide at the toe as well as the increase pore pressure acting on the sheet piles.

Table 1 Typical Bore Hole at Maumere City BH-7 [18]

Depth (m)	Soil Description	Soil Classification	N_{SPT}	D_{50} (mm)	% Finer
0.00 - 2.00	Sand, dark grey, fine to medium grained, medium dense	Dark grey / Sand	8	0.24	5.3
2.00 - 4.00	Sand, dark grey, fine to medium grained, medium dense. At 3.45 - 3.80 m : light grey	Dark grey / Sand	14	0.23	4.9
4.00 - 5.00	Sandy silt, trace of coral, soft	Grey / Sandy Silt	3	0.17	16.9
5.00 - 7.00	Sand, grey, mixed with shell and coral, grained diameter 2 cm, very loose	Grey / Sand	1	0.08	49
7.00 - 8.00	Sandy silt, grey, mixed with coral, diameter 2 - 4 cm, soft	Grey / Clayey Sandy Silt	2	0.02	73.1
8.00 - 9.00	Sandy silt, grey, mixed with coral, diameter 2 - 4 cm, soft	Grey / Gravelly Silty Sand	1	0.28	32.4
9.00 - 12.00	Silty sand, grey, mixed with coral, grained diameter 6 cm, stiff	Grey / Silty Sandy Gravel	6	0.45	32.1
12.00 - 13.00	Sand, grey, medium to coarse grained, loose	Light grey / Silty Sand	34	0.18	30.1
13.00 - 15.00	Sandy silt, coarse grained, dense to very dense, mixed with coral & gravel, light grey	Grey / Gravelly Sandy Silt	14	0.28	36.7
15.00 - 17.00	Sandy silt, light grey, mixed with coral & gravel, coarse grained, dense to very dense	Light grey / Sandy Silt	51	0.26	23.6
17.00 - 20.00	Sandy silt, light grey, mixed with coral & gravel, coarse grained, dense to very dense. At 17 m depth trace with 5.5 - 9.5 cm diameter of coral limestone	Light grey / Sandy Silt	11	0.32	29.8
20.00 - 22.00	Sandy silt, light grey, mixed with coral & gravel, coarse grained, dense to very dense	Light grey / Gravelly Silty Sand	6	0.67	19.4
22.00 - 23.00	Sandy silt, light grey, mixed with coral & gravel, coarse grained, dense to very dense	Light grey / Silty Sand	49	0.32	29.1
23.00 - 26.00	Sandy silt, grey, mixed with 3 cm diameter of limestone and gravel	Light grey / Sandy Silt	29	1.11	14.4
26.00 - 28.00	Sandy silt, light grey, coarse grained	Light grey / Sandy Silt	19	0.19	30.7
28.00 - 29.00	Sandy silt, trace with 7.5 cm diameter of limestone and gravel	Light grey / Sandy Silt Gravel	>50	1.3	

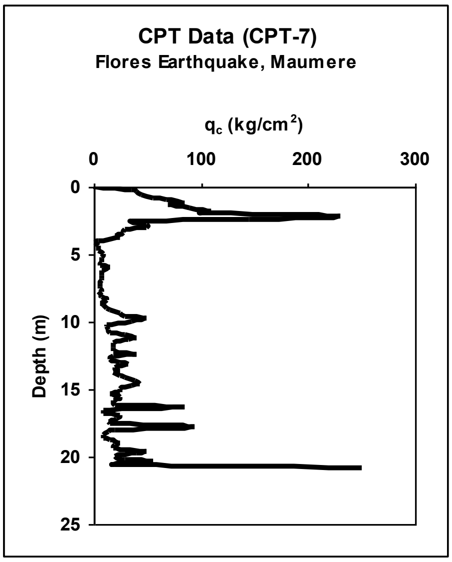

Fig. 28 CPT result in Maumere City [18].

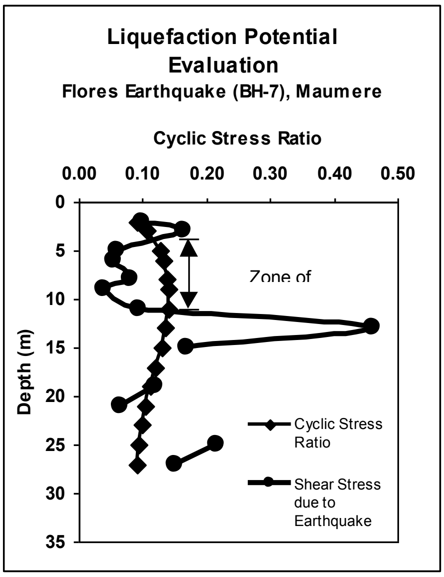

Fig. 29 Liquefaction potential of Maumere City soil deposit [18].

14. Failures of Earth Reinforced Embankments

Two major projects on reinforced earth slope occur in West Java. The first one was at Cikarang where the slope is in the bank of the drainage canal. The failures were caused by softening of the soil inside geotextile as water penetrated into it. As a result, frictional resistance between the geotextile material and the soil significantly decreases and sliding could not be avoided.

Two houses on top of the slope damaged due to the movement of the soil. Based on this lesson, the developer redesign and reconstruct the slope using approach that geotextile is not to be used in combination with expansive soil. The rehabilitation of the slope was by lining along the canal.

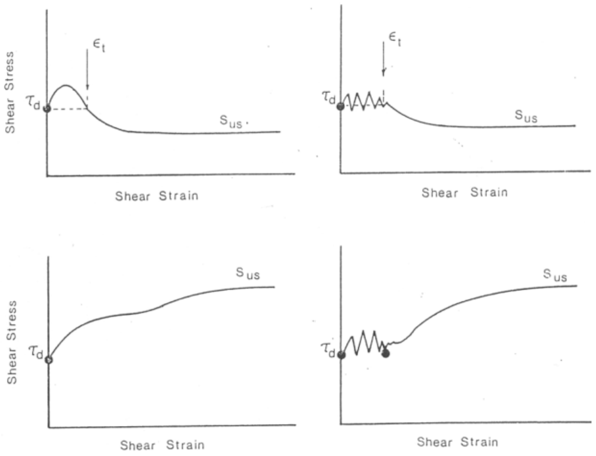

Fig. 30 Stress strain behavior of saturated sand under monotonic and cyclic loading [4]

Fig. 31 Failures of sheet piles due to liquefaction (photographic documentation, Rahardjo)

The second major project of geotextile reinforced earth failures occurred at Cibubur, West Java, where the very high slope was constructed up to 27 m. The slope was made from 14 layers of geotextile encased soil compacted in the field. The failures were initiated by sliding of the toe, which is indicated as bearing capacity failures. The failure was at the lower layer where the soil used for fill was red clay, which after compaction is expected to achieve cohesion value of 0.5 kg/cm^2. However, theoretically, even if this strength is achieved, the bearing capacity of the bottom layer will not be sufficient to carry the load of the fill. Another expected cause of this slide may be the existence of ground water, which flow freely under gravity and were blocked by the fill placement. This action causes accumulation of the ground water behind the reinforced earth structure and soften the fill material as well as generating water pressure on the structure. Based on study by Rahardjo [19], an indication of the bearing capacity failure is revealed through modeling of the staging of construction using finite element analysis (Fig. 36).

Fig. 32 Failures of earth reinforced embankments (photographic documentation, Rahardjo).

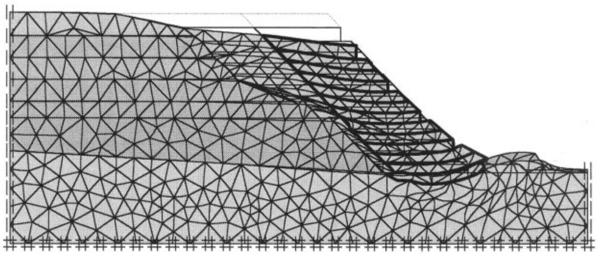

Fig. 33 Simulation of failures of reinforced earth slope [19].

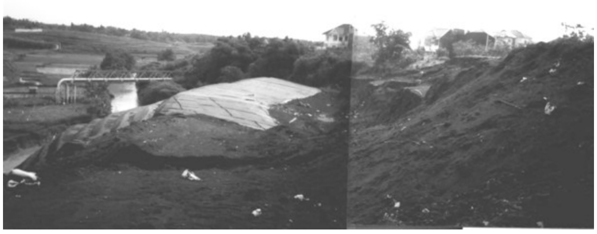

Fig. 34 View of the slope failures from the river (photographic documentation, Rahardjo).

15. New Insights on Slope Stability Analysis

The practice of slope stability analysis in general has the aims of defining the safety of a slope. Most of the analysis is based on the limit equilibrium method, which has the assumption of the equilibrium of solid body. This assumption is not always correct since in soft soil the mass is not rigid, instead deformable. Also in the ordinary analysis, the pore pressure is defined based on hydrostatic pressure; on the other hand in fill embankment, the pore pressure shall include the development of excess pore water pressure.

In a more modern approach, the safety factor is considered at every point of the sliding plane using the ratio of the shear strength of the soil and the mobilized strength required for equilibrium. This method requires the knowledge of stress path specially when effective stress analysis is involved.

In case of natural slope, slope stability analysis is directed towards understanding the development and form of natural slopes and the processes responsible for different natural features. It should be taken into account that the engineering properties of the soil might undergo changes due to increase of water content and weathering. It is also important when the natural slope is undergoing movement, residual shear strength shall be used instead of peak shear strength. Of particular interest is the shear strength back calculated from the geometry and the occurrence of the slides.

In most projects that require the construction of embankment, slope stability analysis is used to assess the stability of slopes under short term (during construction) and long-term conditions. Many cases in Indonesia only consider short-term analysis. It is interesting that for very soft to soft soil, overburden and degree of consolidation significantly increase the shear strength and hence the analysis should modify the shear strength accordingly.

When assessing the slope stability of engineered slopes, the sequence of construction shall be considered including time or schedule of action. This type of analysis his is generally conducted when there is development of an area for projects or certain condition that is expected to be potential to slope failures.

There is a trend in research to analyze landslides to understand failure mechanisms and the influence of environmental factors. Most of this type of study is more on academic level and hence mostly done by Indonesian university staff.

To enable the re-design of failed slopes and the planning and design of preventive and remedial measures, understanding a failure mechanism is very important for all aspects of the mechanism were seldom considered in a proper way.

16. Conclusions Summary

- Indonesia has many constructions located in soft soils. Failures have occurred due to negligence and lack of knowledge of soft soils engineering.
- Forensic geotechnical investigations often reveal the reality and provide important lessons.
- Corrective methods involve specialty construction techniques that must be understood by all parties involved and shall be modeled in realistic ways. An understanding of geology, ground water and the effect of water in soils, and soil properties are of central importance.
- Analysis must be based upon a model that accurately represents subsurface conditions, ground behavior and applied loads. Judgments regarding acceptable risk of safety factors must be made to assess the results of analysis.
- The geotechnical analysis shall take into account a variety of factors relating to topography, geology, and material properties, often relating to whether the soils was naturally formed or engineered. The construction sequence shall be defined clearly and at each stage the stability shall be assessed.

17. References

[1] Abramson, W. Lee, T.S., Sharrna, S., and Boyce, G. M. *Slope Stability and Stabilization Methods*, John Wiley & Sons, New York, (1996).

[2] Anderson, M.G., and Kneale, P. E. Prediction of Pore Water Pressure and Soil Suction Conditions in Road Cut Slopes in St. Lucia, West Indies: A Methodology to Aid Cut Slope Design. *Transportation Research Record 965: Soil Reinforcement and Moisture Effects on Slope Stability*, National Research Council, (1984).

[3] Bjerrum, L. Mechanism of Progressive Failure in Slopes of Overconsolidated Plastic Clay Shales. preprint, *ASCE Structural Engineering Conference*, Miami, (1966).

[4] Castro, G. On the Behavior of Soils During Earthquake – Liquefaction. *Soil Dynamic and Liquefaction, Developments in Geotechnical Engineering*, Volume. 42, Ed. by Cakmak, A.S., Elsevier, (1987).

[5] Cox, J.B. The Distribution and Formation of Recent Sediments in South East Asia. *Proceeding 2nd South Esia Conference on Soil Engineering*, (1970). pp. 30-47.

[6] Departemen Pekerjaan Umum, Petunjuk Perencanaan Penanggulangan Longsoran*, (Manual on Design and Rehabilitation of Landslides)*, SKBI-2.3.06.1987, Yayasan Badan Penerbit PU, Jakarta, (1987).

[7] DiMillio, A.F., and Strohm Jr., W.E. Technical Guidelines for the Design and Construction of Shale Embankments. *Transportation Research Record 790, - Shale and Swelling Soils*, Washington, DC, National Research Council, (1981).

[8] Directorate of Geology and Vulcanology. *Geological Map of East Kalimantan*, (2001).

[9] Hannon, J.B., and Forsyth, R.A. Performance of an Earthwork Reinforcement System Constructed with Low Quality Backfill. *Transportation Research Record 965: Soil Reinforcement and Moisture Effects on Slope Stability*, National Research Council, (1984).

[10] Peck, R.B. Stability of Natural Slopes. *Journal of Soil Mechanics and Foundation Division,* ASCE, Volume 93, No. SM.4, (1967), pp. 403-417.

[11] Rahardjo, P.P., and Salim, E. Manual Kestabilan Lereng, (Manual on Slope Stability Studies) *Publikasi Geotechnical Engineering Center,* Universitas Katolik Parahyangan, (1995).

[12] Rahardjo, P.P. Resiko Geoteknik pada Bangunan Struktur Bawah dan Struktur Tanah yang Tertunda dalam Masa Konstruksi, (Geotechnical Risks on the Substructures and Soil Structures Due to Delay during Construction Period), *Proceeding of Seminar Industri Konstruksi Di Era Krisis, Ikatan Alumni Teknik Sipil,* Universitas Katolik Parahyangan, Bandung, (1998).

[13] Rahardjo, P.P., and Meilani, I. Effect of Saturation on the Strength of Natural and Compacted Padalarang Clays. *Research Report, Geotechnical Engineering Center*, Parahyangan Catholic University, (1999).

[14] Rahardjo, P.P. Landslide Evaluation and Measures at PT. Indorama. *Report to PT. Indorama*, (1999).

[15] Rahardjo, P.P., Margono, M., and Widjaja, B. Penelitian Clayshale di Bukit Sentul, Bogor, (Research on Clayshale at Bukit Sentul, Bogor). *Journal HATTI*, Volume 4, (2001).

[16] Rahardjo, P.P. Pelajaran dari Kegagalan Geoteknik, (Lessons learned from Geotechnical Failures). *Proceeding, Pertemuan Ilmiah Tahunan V, HATTI*, Bandung, (2001).

[17] Rahardjo, P.P. Evaluasi dan Desain Rehabilitasi untuk Penurapan di Kuto Besak, Palembang, (Evaluation and Design Rehabilitation of Sheet Piles at Kuto Besak, Palembang). Research Report, Bandung, (2001).

[18] Rahardjo, P.P., and Meilinda, L. Prediction of Liquefaction Settlement Based on Cone Penetration Test Data. *Proceeding, International Conference on In situ Measurement of Soil Properties and Case Histories*, Bali, (2001).

[19] Rahardjo, P.P. Resiko Geoteknik dan Investigasi Forensik pada Longsoran (Geotechnical Risks and Forensic Investigation on Avalanches), *Proceeding of Seminar Nasional SLOPE*, Bandung, (2002).

[20] Rahardjo, P.P. Prediction of the Degree of Consolidation of Reclamation on Deep Deltaic Soils using CPTu. *Proceeding 3rd International Conference on Stress Deformation Characteristics*, Atlanta, USA, (2004).

[21] Rahardjo, P.P. Geotechnical Forensic Investigation Report on the Failures of Nenang Besar Bridge. *Research Report*, (2013).

[22] Schuster, R.L., and Krizek, R.J. Landslides Analysis and Control. *Special Report 176, Transportation Research Records*, National Research Council, Washington, DC, (1978).

[23] Strohm, W.E., Bragg, G.H., and Ziegler, T.W. Design and Construction of Compacted Shale Embankments. *Technical Guidelines. Federal Highway Administration, US Department of Transportation*, Volume 5. FHWA-RD-78-141, (1978).

[24] Sutikno. Tanah Longsor Goyang Pulau Jawa. (Landslides Move Java Island), *Harian Kompas*, Indonesia, November 19, (2001).