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Collapse and Erosion of Khon Kaen Loess with Treatment Option

By

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ABSTRACT

Khon Kaen loess is one of the problematic soils in the Northeastern region of Thailand. The soil has a potential to collapse, which has been caused by wetting. This study reports the characteristics of Khon Kaen loess under saturated and unsaturated conditions. From laboratory testing results, shear strength of Khon Kaen loess increases linearly with matric suction at low suction pressure and remains constant beyond the residual suction. Its relationship gives ϕ^b parameter of 32 degrees. Since Khon Kaen loess exists in abundance and covers a very large area of the region, this study aims to investigate the suitability of this soil as a material for road construction. A series of trial slope embankments were constructed in order to evaluate the behavior of the loess. The field observations showed that the testing embankment was stable under traffic loading and erosion of soil occurred by water infiltration from ground surface. The trial embankment reinforced with geosynthetic materials was also tested. The results showed the effectiveness of geosynthetic material as one of the remedial measures.

1. INTRODUTION

Loess is known in civil engineering as one of the major problem soils because of its collapse and sudden decrease in volume of voids which has caused severe settlement problems for many structures founded on it. The loess terrain exists in abundance in the Northeastern region of Thailand. The loess deposits can be classified into two, Red Loess and Yellow Loess (Phien-wej et al., 1992). Lithologically and mineralogically, the two units are similar but different in oxidation states causing color difference. The thickness ranges from a few meters to more than 6 m. Thick loess deposits are found in high elevation areas of the region including Khon Kaen, which is the economic center of the upper region (Fig.1). Firstly, the soil was considered as a good bearing layer. Sarujikumjonwattana et al. (1987) found that wetting of the soil by leaking water from drains and sewers caused the severe settlement and damage of the irrigation structures and low-rise buildings.

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In this study, the properties of Khon Kaen loess are presented under saturated and unsaturated conditions. Trial embankments are also tested. The objectives of this test were to provide a case record and to evaluate the potential of the soil as a material for road construction.

2. SOIL PROPERTIES

A series of laboratory tests were carried out on red loess unit. The samples were from outcrop found in Khon Kaen University, where several foundation problems associated with this soil had occurred. Undisturbed samples of the soil were taken by means of block sampling. The samples were carefully trimmed and waxed from the bottom of excavated pits (Fig.2). The tests were initially conducted on the soil under in situ water content, after which the soil was wetted by water infiltration from the ground surface. In the laboratory tests, engineering properties of the loess were investigated through index tests, the direct shear test, the oedometer test and the saturated and unsaturated triaxial compression test.

2.1 Index properties

Index properties of Khon Kaen loess are summarized in Table 1. The soil is silty fine sand (SM). The loess consists of 65% sand, 30% silt and 5% clay (Fig.3). Udomchoke (1991) studied the microstructure of this soil and found that Khon Kaen loess consists of well-sorted fine sand grains but poorly sorted silt and clay particles. Sand grains have smooth, sub-rounded surfaces indicating eolian origin. The skeleton grains are held together by means of cementation of clay matrice in the form of clay bridge bonds. Most of the clay content, which is predominantly kaolinite, is present in the form of a surface coating on coarse grains.

2.2 Direct shear test

The direct shear test is the simplest, the oldest and the most straightforward procedure to measure the short term shear strength of soil in terms of total stresses. To obtain the strength parameters c and ϕ of the soil, the direct shear tests were performed with natural undisturbed samples and pre-wetted samples with various depths of soil layers. In the experiment, the direct shear tests were performed under unconsolidated undrained condition. Figure 4 shows the strength parameters c and ϕ with depth.

2.3 Compressibility of soil

The oedometer test is used for the determination of the consolidation characteristics of soils of low permeability. Analysis of data from tests is presented as a standard conventional procedure to explain the compressibility of soils. However, the loess is naturally unsaturated. In the test, the unsaturated undisturbed and remolded samples were subjected to the axial load in the oedometer box without the swelling process. Figure 5 shows the comparison of the compressibility characteristic between undisturbed and remolded sample. From the curve of undisturbed sample, the compression index is 0.0135 with maximum past pressure of 1334 kPa. The compression index of remolded sample is only half of the undisturbed sample. In the section of unsaturated soil, the results from modified oedometer test with soil suction control will be shown.

2.4 Triaxial compression test

Series of triaxial compression tests were carried out to obtain strength parameters of the loess under various consolidation pressures. Specimens prepared from cylindrical samples 50 mm in diameter were used. The tests conducted in this study were the consolidated-undrained test. Figure 6 shows the triaxial test setup and the strength envelop of the three tests. From the experimental results, the Mohr-Culomb shear failure envelope gives a c' value of approximately zero and ϕ' of 38 degrees.

2.5 Unsaturated soils

A theoretical framework for unsaturated soil mechanics widely accepted in geotechnical engineering is the concept of stress state variables introduced by Fredlund and Morgenstern (1977). Unsaturated soil behaviors could be explained in terms of two independent stress state variables (i.e., net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$). The shear strength equation for unsaturated soils proposed by Fredlund et al. (1978) has been accepted widely in geotechnical engineering and is given as,

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad (1)$$

where, τ = shear strength, c' = effective cohesion intercept, σ = total normal vertical stress, ϕ' = effective angle of internal friction with respect to net normal stress, u_a = pore-air pressure, u_w = pore-water pressure, ϕ^b = angle of internal friction with respect soil suction.

2.6 Soil-Water Characteristic Curve

The SWCC can be described as a measure of the water –holding capacity (i.e. storage capacity) of the soil, when subjected to various values of suction. Changes in soil, water and air phases take on different forms and influence the engineering behavior of unsaturated soils. The relationship between amount of soil water and soil suction was evaluated using a pressure plate apparatus and vapor equilibrium technique (Fig.7). The soil-water characteristic curve for Khon Kean loess was tested from a saturated condition to a totally dry condition (i.e. for soil suctions ranging from 0 to 1,000,000 kPa) and was shown in Fig.8. The air-entry value can be obtained by extending the constant slope portion of the soil-water characteristic curve to intersect the suction axis at saturated condition. Evaluated air-entry value for the soil is 27 kPa. When matric suction exceeds the air-entry value, desaturation starts in the liquid phase. The soil dries rapidly with increasing suction.

2.7 Triaxial for unsaturated soil

Figure 9 shows the schematic diagram of modified triaxial apparatus for unsaturated soil. A series of unconsolidated-undrained triaxial tests were carried out in order to find the ϕ^b value. The shear strength under constant net normal stress and varying matric suction are summarized in Table 2. Figure 10 (a) shows the relationship between shear strength and matric suction up to 100 kPa. An extended Mohr-Colomb equation (Eq.1) is used to interpret the test results. When matric suction is zero (saturated condition), the shear strength is calculated as 820 kPa with c' equal to zero, ϕ^b equals to 32 degrees under a constant net normal stress of 200 kPa. The shear strength data of Khon Kaen loess subjected to high suctions are presented in Fig.10 (b). A constant net normal stress of 200 kPa was applied with various total suctions. The suctions applied were always larger than the residual suction of 500 kPa. Figure 10 (b) shows that shear strength of Khon Kaen loess remains constant beyond residual soil suction.

2.8 Modified oedometer test

The relationship between the volume change and loading conditions of unsaturated soil can be illustrated by the modified oedometer test result. The test aims to obtain the volume change characteristic of the soil with different matric suctions compared to the saturated condition. The modified oedometer apparatus is schematically shown in Fig. 11. The specimen is subjected to air pressure through a top cap. The burette connected with high air entry ceramic disk at the bottom base can measure the drained water. The $e - \log p$ curve is shown in Fig. 12. The curves show that the deformation characteristic of the unsaturated soil is flatter than that of the saturated soil. Under the same pressure, the settlement of saturated soil is larger than the unsaturated one.

3. TRIAL TEST EMBANKMENT

Evaluation of slope instability is an inter-disciplinary effort requiring contributions from engineering geology and soil mechanics. The main objectives of the slope analysis of Khon Kaen loess embankment are to assess the stability of slope under given conditions and to assess the potential of the soil as a material for road construction. Natural slopes in soil are of interest to geotechnical engineers. The soil composing any slope has a natural tendency to collapse under the influence of gravitational and other forces. Figure 13 shows agricultural pond in Khon Kean University before and after raining. The collapse and erosion phenomenon of the loess are evident in Fig 13 (b).

3.1 Site conditions and design of trial embankment

The test site is located in Khon Kaen University. The construction area chosen was flat for the most part and near the borrow pits of fill material. The design of the test embankment configuration was based on the typical section from Department of Highway, Thailand. The final layout of the fill and the cross section of the embankment are shown in Figs.14 and 15, respectively. The test area is divided into two parts to simulate the general traffic load of 2 t/m^2 and to simulate the rainy season in the Northeastern region of Thailand as shown in Fig. 16 and Fig. 17. To facilitate monitoring of the construction and to observe the performance of the embankment, field instruments were installed. The instrument layout was selected based on the results of the limit equilibrium analysis and the total number of instruments. The instrumentation of unreinforced slope consists of piezometers, total pressure cells and inclinometer casings. Pneumatic piezometers were installed to monitor the positive and negative pore pressures. The pneumatic-type total pressure cells were installed to measure the total pressure imposed by the fill on the bottom of the embankment. The applied total stresses measured from the monitoring agreed well with those deduced based on the thickness of fill and the measured unit weight of the fill. Horizontal movement of the ground was monitored by measuring the displacement from inclinometer.

3.2 Embankment construction

The Khon Kaen loess was used as a fill material. The fill unit weight, as determined by in situ tests, averaged 20.2 kN/m^3. The natural water content of the fill was 6%. A series of soil layers were constructed with a thickness of 0.5 m. Field density measurements on the layers indicated an average unit weight of 18.5 kN/m^3. After reaching a designed thickness of 2.5 m, the first half of the trial embankment was statically loaded with dead weight of 2 t/m^2. The staged loading is 0.333 t/m^2 in steps. The second half of the embankment was soaked with water to simulate flood after a heavy rainfall.

3.3 Performance of trial embankment and results

A number of instruments were installed to provide warning of any potential failure. These instruments which recorded minute movements were monitored during and post construction. The variations of horizontal displacement with depths obtained from inclinometers are shown in Fig. 18 (a) and 18 (b). At the end of simulation processes, maximum horizontal displacement of about 1 mm and 8 mm were found from loading area and soaked area, respectively.

The embankment was found to stand free at a slope of about 53° . The displacement profile at 2.5 m embankment thickness did not indicate any failure zone. The soils in the soaked area suddenly dropped after being soaked for 20 days as caused by the water infiltration (Fig.19). The erosion continued to occur as more water was added. The variations of excess pore water pressure with time for different pneumatic piezometers placed below the fill were recorded (Fig. 20). The excess pore pressures in all the piezometers were small up to the end of construction. A small increase in the excess pore pressure is observed in response to the infiltration of water from the top surface of the embankment. The excess pore water pressure responses indicated by piezometer 2 and 3 were very similar even though the piezometers were placed at different depths.

3.4 Treatment option

To enable the redesign of failed slope, the planning and design of preventive and remedial measures were necessary. The second phase of trial embankment was constructed. A single layer of geogrid and bi-dimensional geojute were used for the reinforcement. The random structures of the geojute hinder particle migration, interlocks with the grass roots while the geogrid is capable of supporting long term tensile loads. Figure 21 shows the stable reinforced embankment. Details of the instrumentation, construction and performance of the reinforced embankment will be provided in a subsequent paper.

4. CONCLUSIONS

The characteristics of Khon Kaen loess have been investigated by both laboratory and field testing. The results of the laboratory tests on undisturbed and remolded samples described in this paper are reported. Strength of the loess decreases as a result of wetting. The research primarily focused on the strength characteristic of the unsaturated soil over a wide range of soil suctions. Suctions were applied using pressure plate apparatus and vapor equilibrium technique. The compacted loess was desaturated to the residual state of unsaturation through the use of chemical salt solutions. The testing results show that the air-entry value of the soil is about 27 kPa. The SWCC also gives that the residual water content and residual suction are 5% and 500 kPa, respectively. The unsaturated triaxial results showed that shear strength of soil increases with matric suction at low suction pressure. Its relationship between shear strength and soil suction in the transition stage gives the ϕ^b of 32 degrees. After the suction exceeds the residual soil suction, the shear strength remains constant (i.e., horizontal failure envelope with respect to soil suction). Using Khon Kaen loess as a material for road construction showed that erosion by water infiltration will cause the soil failure of fill embankment. Geosynthetics material used as a reinforcement is one of the alternatives to stabilize the embankment.

ACKNOWLEDGEMENT

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Table 1 – Index properties of Khon Kaen loess

Property	Khon Kaen Loess
Specific gravity	2.60
Natural dry unit weight (kN/m^3)	15.3
Natural water content during rainy season (%)	8-12
Liquid limit (%)	16.0
Plastic limit (%)	13.0
Plasticity index	3.0
Soil classification (USCS)	SM
Optimum moisture content (%)	9.7
Maximum dry density (kN/m^3)	21.1
Permeability coefficient (cm/s)	2.80×10^{-6}

Table 2 – Summary of stress conditions during unsaturated triaxial tests

Net normal stress (kPa)	Soil suction (kPa)	Shear strength (kPa)
200	0	820
200	40	837
200	64	870
200	69	867
200	100	880
200	9,800	1,069
200	83,400	1,349
200	296,000	1,460

Fig.1 – Areas of loess deposits (stippled area) in Thailand (after Phien-wej et al. 1992)

(a) Block sample

(b) Excavated pit

Fig. 2 – General view of a test pit at Khon Kaen University

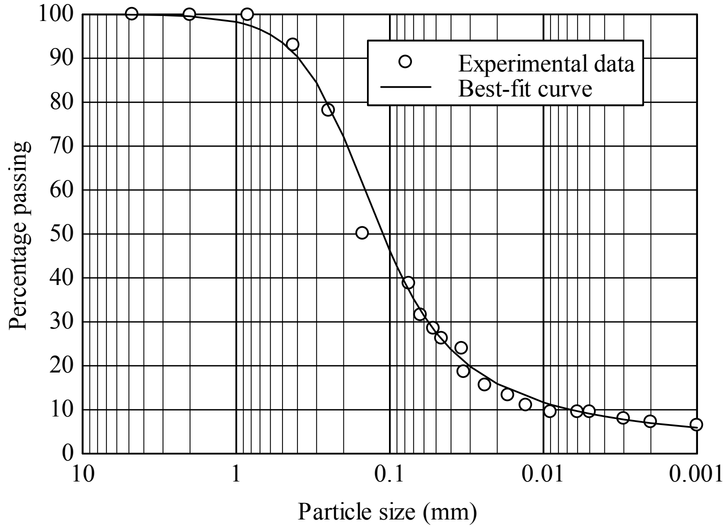


Fig. 3 – Particle size distribution of Khon Kaen loess

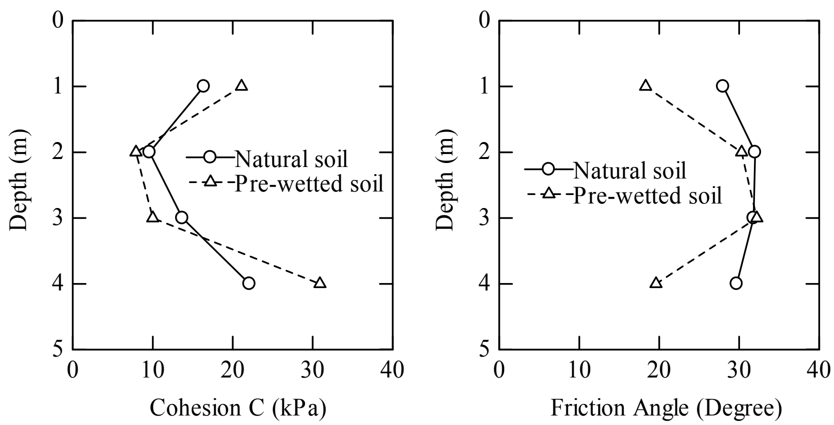


Fig. 4 – Summary of direct shear tests of undisturbed sample

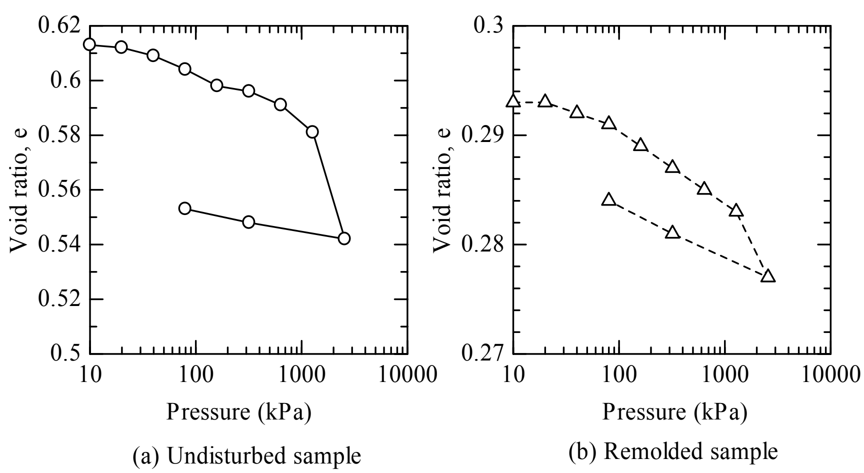
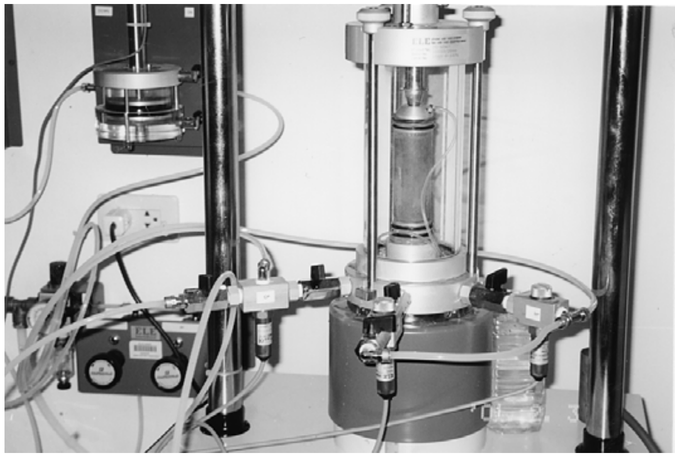
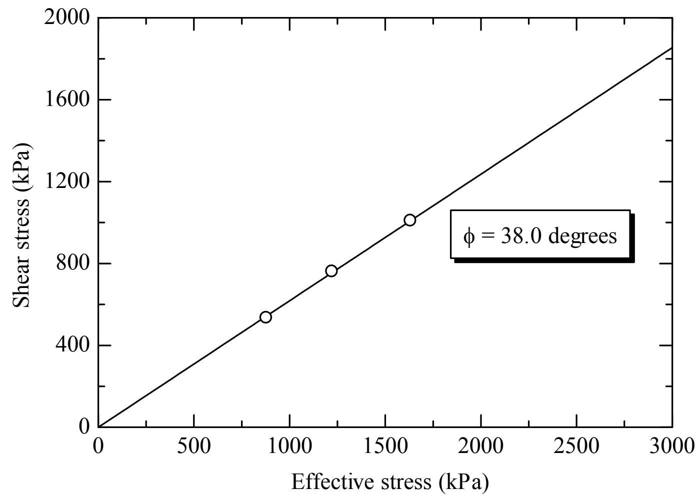


Fig. 5 – Oedometer test results

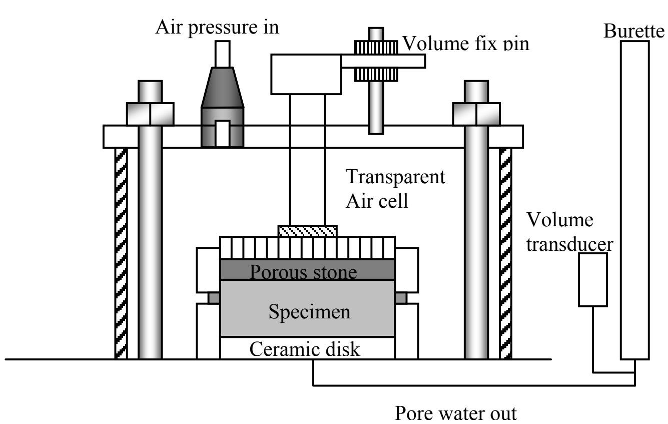


(a) Test setup

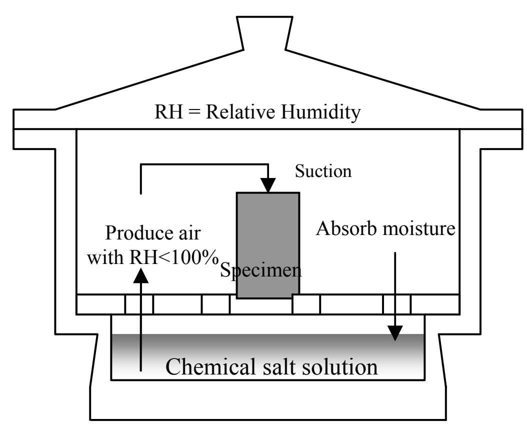


(b) Test result

Fig. 6 – Triaxial compression test results from undisturbed samples



(a) Pressure plate apparatus



(b) Vapor equilibrium technnique

Fig. 7 - Apparatus for SWCC test

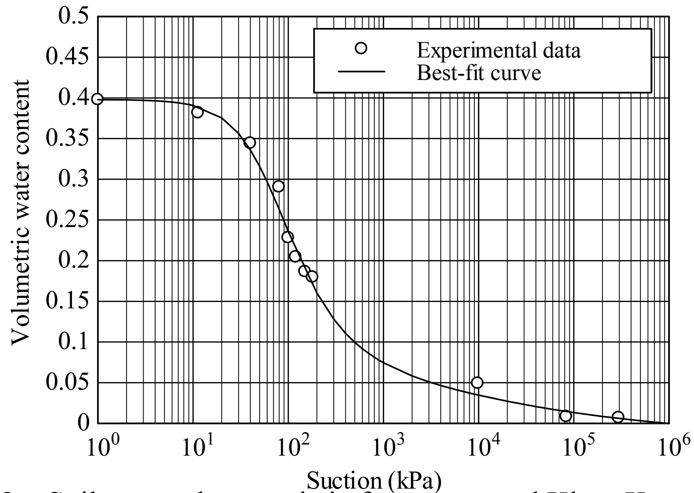


Fig. 8 – Soil water characteristic for compacted Khon Kaen loess

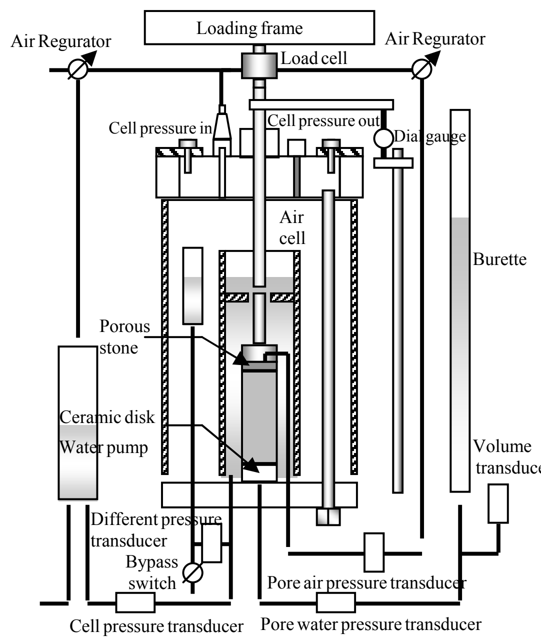
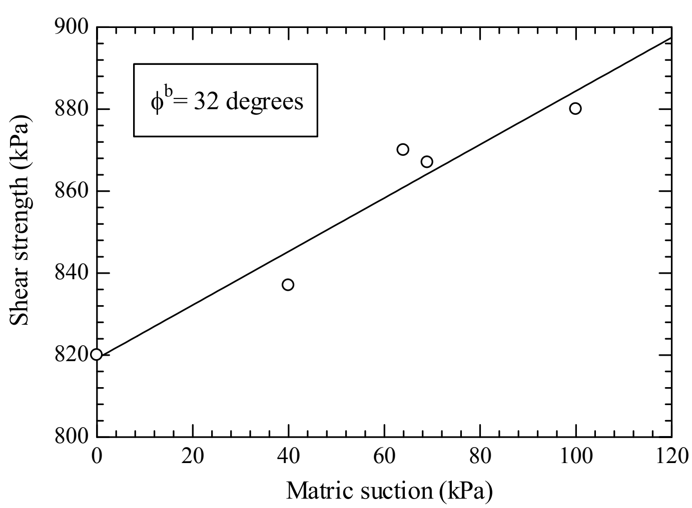
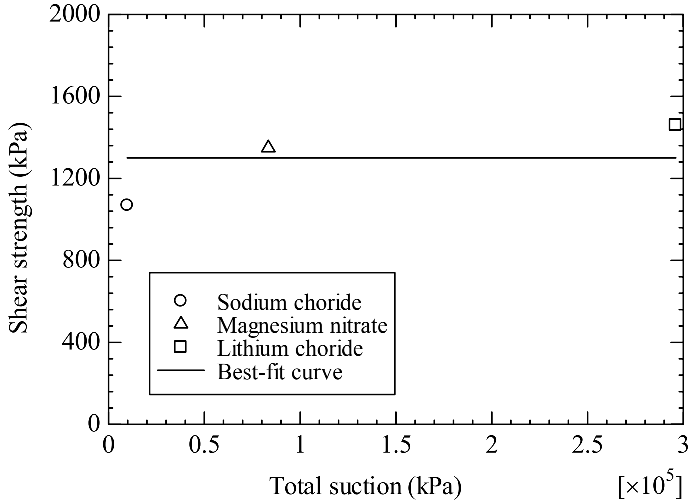


Fig. 9 - Schematic of modified triaxial apparatus for unsaturated soil



(a) Relationship between shear strength and matric suction at a constant net normal stress of 200 kPa



(b) Relationship between shear strength and high suction a net normal stress of 200 kPa

Fig. 10 – Shear strength versus metric suction

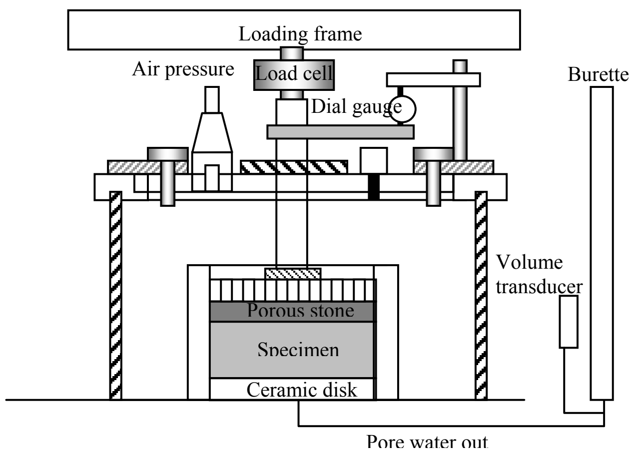


Fig. 11 – Modified oedometer apparatus for unsaturated soil

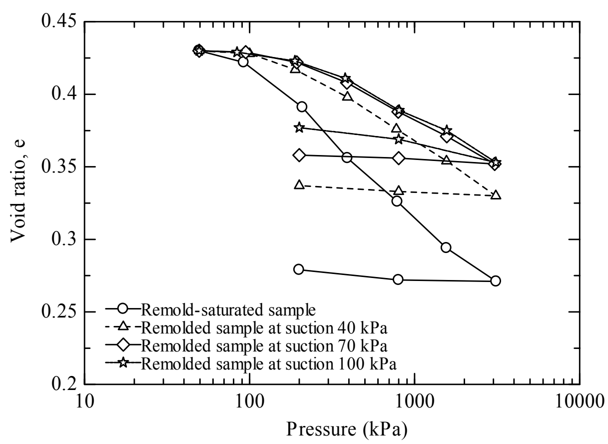
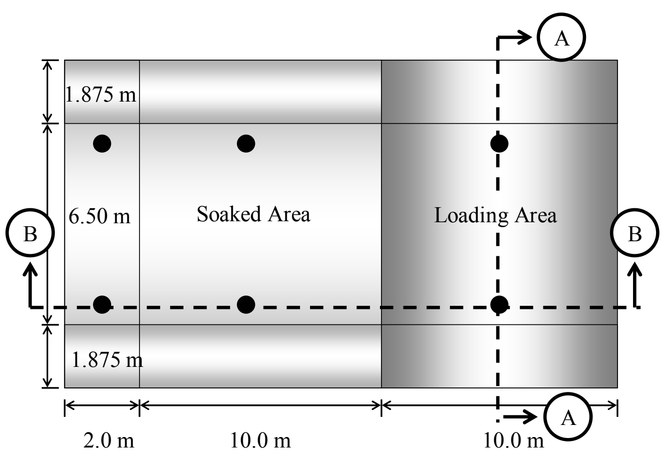


Fig.12 – Oedometer test result from remolded samples

(a) Before (b) After

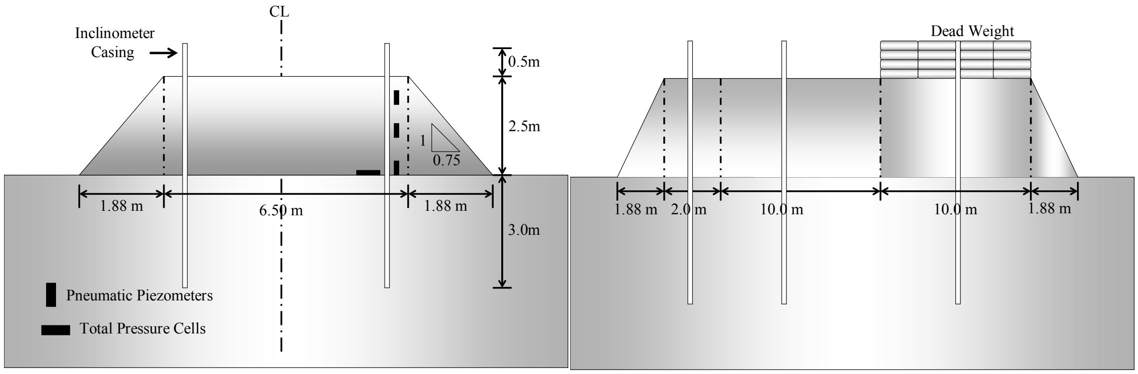
Fig. 13 – Collapse and erosion of agricultural pond

Fig. 14 – General view of trial embankment



(a) Plan view

Fig. 15 – Cross section of the embankment



(b) Section A-A

(c) Section B-B

Fig. 15 – Cross section of the embankment

Fig. 16 – Simulation of load by dead weight

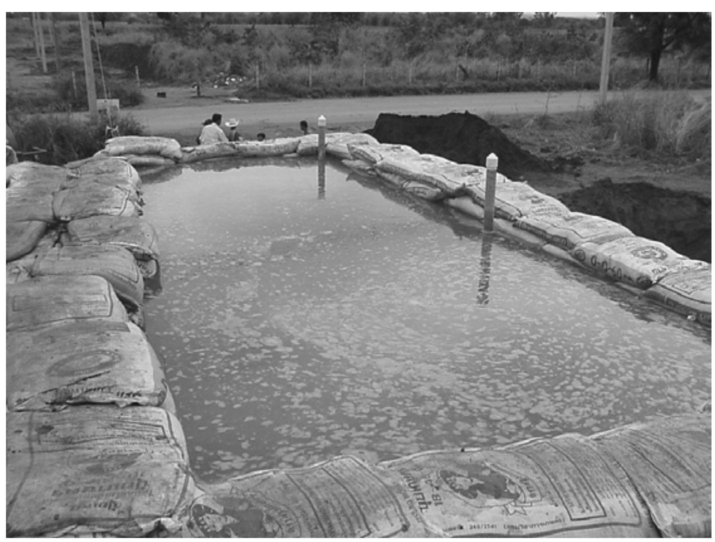
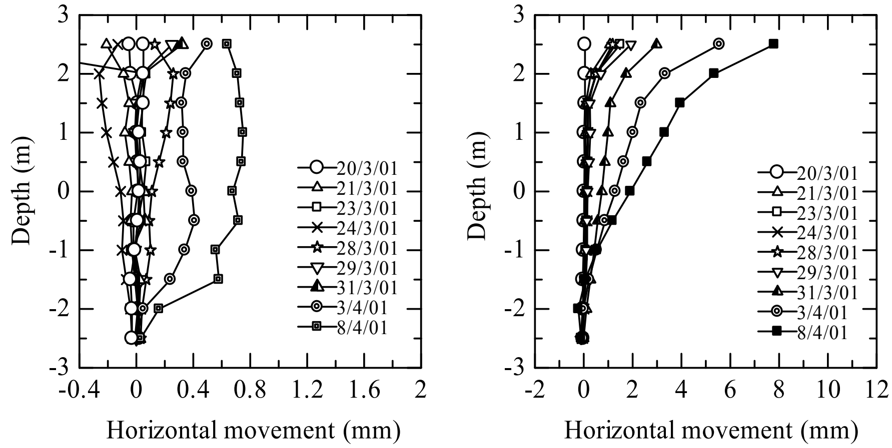


Fig. 17 – Soaking process



(a) Loading area (b) Soaked area

Fig.18 – Horizontal movement of the embankment

Fig. 19 – Erosion failure of trial embankment

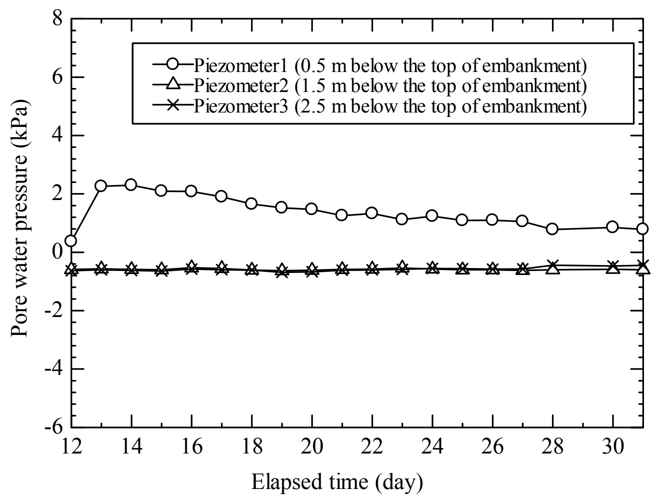


Fig. 20 – Pore pressure distribution in the embankment erosion process

Fig. 21 – Reinforced embankment