Shear Deformation development and the Increase of Pore Pressure due to Rainfall Infiltration in Sandy Model Slope with Different Inclination

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ABSTRACT: Monitoring of surface displacement of slope has been widely adopted as time prediction method of shallow landslide due to rainfall. Modeling of shear deformation according to rainfall infiltration is necessary for establishment of the method. In order to examine the constitutive relation for the model, surface displacement, pore pressure at the base, volumetric water content (hereafter, V.W.C.) and suction, shear strain in the sandy model slope are monitored during artificial rainfall. Analysis of the monitored data shows that surface displacement and shear strain in the slope proceed at small rate under unsaturated condition first, then increase remarkably with the rise of pore pressure. Unsaturated component of surface displacement of steeper slope is larger than that of gentler slope. It is likely to be due to that shear strain with the increase of suction is larger in steeper slope while shear strain according to the increase of pore pressure is larger in gentler slope.

Keywords: Shallow landslide, Rainfall, Shear strain, Pore pressure, Suction

1. INTRODUCTION

The modeling of shear deformation of steep slope due to rainfall infiltration is necessary for the establishment of time prediction method of shallow landslide due to rainfall. Observations of deformation of the slope under artificial rainfall or specimen under anisotropic condition just before the failure had been implemented by some researchers [1]-[3], and produced the empirical law between time and deformation. The law has been adopted as the time prediction method based on the monitoring surface displacement [2], [3]. Because this method is empirical one, it does not take the change of stress in the slope into consideration. So it often failed to predict the time of failure of the slope under sudden change of rainfall intensity.

Recently some researches [4], [5] tried to observe slope deformation by Microelectro-mechanical system (MEMS) tilt-meter under the change of geometry of the slope such as cutting works, and other researches [6], [7] observe the deformation of the slope under artificial rainfall. Although they made much efforts to measure the slope deformation, they could not examine the mechanical law of the slope deformation.

In order to examine the constitutive law for the deformation of the slope under rainfall, the monitoring of V.W.C., suction, shear strain, pore pressure, and surface displacement are measured in the sandy model slope under constant rainfall in this paper. And some consideration are made in order to derive the relation between V.W.C., suction and shear strain, or that between shear strain and pore pressure in the slope under rainfall infiltration.

2. METHODOLOGY

2.1 Model slope and monitoring devices

Fig.1 shows the longitudinal section of the model slope and location of monitoring devices with slope angle of 30deg. Model slope is made in a flume of 300cm length, 150cm width, and 50cm height at horizontal section, and 600cm length, 150cm width, and 50 cm depth at slope section (Fig.2). The flume has vertical steel blades of 1cm height located every 50cm in the longitudinal direction at the base of the slope in order to prevent slip between the soil mass and the base. Model slope is made of granite soil (Fig.3). The soil is filled and compacted horizontally at every 20cm thickness due to human stepping on the soil, and is managed to keep void ratio of 1.46~1.52. Water content of the soil layer is 3.7~4.4%. The soil layer thickness is 50cm so that soil depth to gravitational direction is 57.7cm The base and upper boundary of the flume is undrained condition, while the lower boundary is drained condition.

In the model slope, soil moisture sensors (expressed as 'VW'
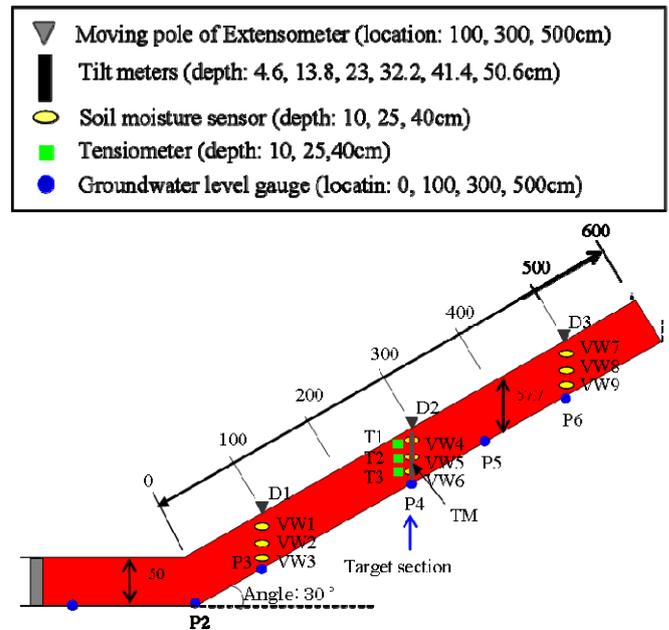
Fig.1 Geometry of model slope and location of monitoring devices (Inclination: 30deg.)

in Fig.1) are installed at the depth of 10, 25, 40cm at 100, 300,500cm from the toe of the slope. They have the accuracy of 0.02 (m^3/m^3). Tensiometers (expressed as 'T' in Fig.1) are installed at the depth of 10, 25, 40cm at 300cm from the toe of the slope. They have accuracy of 1(kPa). Shear strain gauge (expressed as 'SS' in Fig.1) is installed at 300cm from the toe of the slope. It is series of tilt meter at every vertical depth of 9.2cm and tilt meters are connected by bolt and nut. So the meters can incline only to slope inclination direction. Shear strain increment at some depth $\Delta\gamma$ is defined as $\tan(\Delta\theta)$, while $\Delta\theta$ is the inclination increment of the tilt meter (Fig.4). Tilt meter has non-linearity of 0.2 degree which corresponds to that of 0.0035 for $\Delta\gamma$. Groundwater level (hereafter G.W.L.) gauges (expressed as 'P' in Fig.1) with the accuracy of 1cmH$_2$O are located at the base of the model at 0, 100, 300, 400, 500cm from the toe of the slope. The measurement data of the gauge at 100, 300, 500cm are used for the examination in this paper. Extensometers are installed at the surface of the slope. The location is 100cm, 300cm, 500cm from the toe of the slope. It has the non-linearity of 0.1mm

2.2 Experimental conditions

2 types of model slope with different inclination 30deg. (Fig.1), 40deg. are prepared for the examination of the influence of the slope inclination to the relation between shear deformation and rainfall infiltration. The arrangement of measurement devices in the slope of 40deg. is just same with that of 30deg. The difference between the slope of 30deg. and that of 40deg. is soil layer depth to gravitational direction at the slope section of the model. Soil layer depth to gravitational direction of 30deg. is 57.7cm, while that of 40deg. is 65.3cm. Artificial rainfall with the constant intensity of 50 mm/h is sprayed from the rainfall simulator above the model slope until the onset of slope failure.

3. RESULTES OF EXPERIMENTS

Fig.5 shows time variation of V.W.C., suction and shear

Fig.2 Flume and model slope

strain in the slope at 300cm from the toe of the slope, G.W.L. occurred at 5150sec. in the model slope of 30deg.. V.W.C. keeps constant just after the start of the experiment, then and surface displacement at 100cm, 300cm, 500cm from the toe

of the model slope with 30deg inclination. Slope failure makes rapid increase earlier with shallower depth, and it continues to be almost constant after rapid rise. After constant value, V.W.C. at 40cm depth increases again at 4300sec. and that at 25cm also increases again at 5000sec., while that at 10cm keeps almost constant. Suction starts rapid decreasing earliest at 25cm at 500sec., then 40cm at 1300sec., and keeps almost constant negative value after that. Suction at 10cm keeps constant just after the start of experiment then makes rapid decrease at 3000sec. then makes second decrease at 6000sec.. Shear strain at each depth is almost zero until 3700sec., then increases rapidly. Shear strain at 4.6cm, 13.8cm, 23cm, and 50.6cm proceeds to positive while that at 32.2cm, 41.4cm proceeds to negative. Negative value may be due to reaction of tilt meter at this depth against large movement of tilt meters at upper or lower location. Time variation of G.W.L. and surface displacement at 100cm is
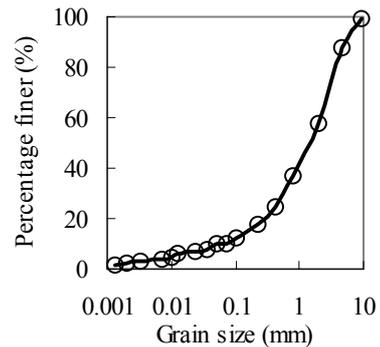
Fig.3 Grain size distribution of granite soil
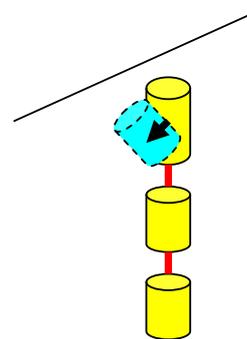
Increase of increment of tilt-meter :$\Delta\theta$

Shear strain increment $\Delta\gamma = \tan(\Delta\theta)$

Fig.4 Measurement of shear strain by tilt meter
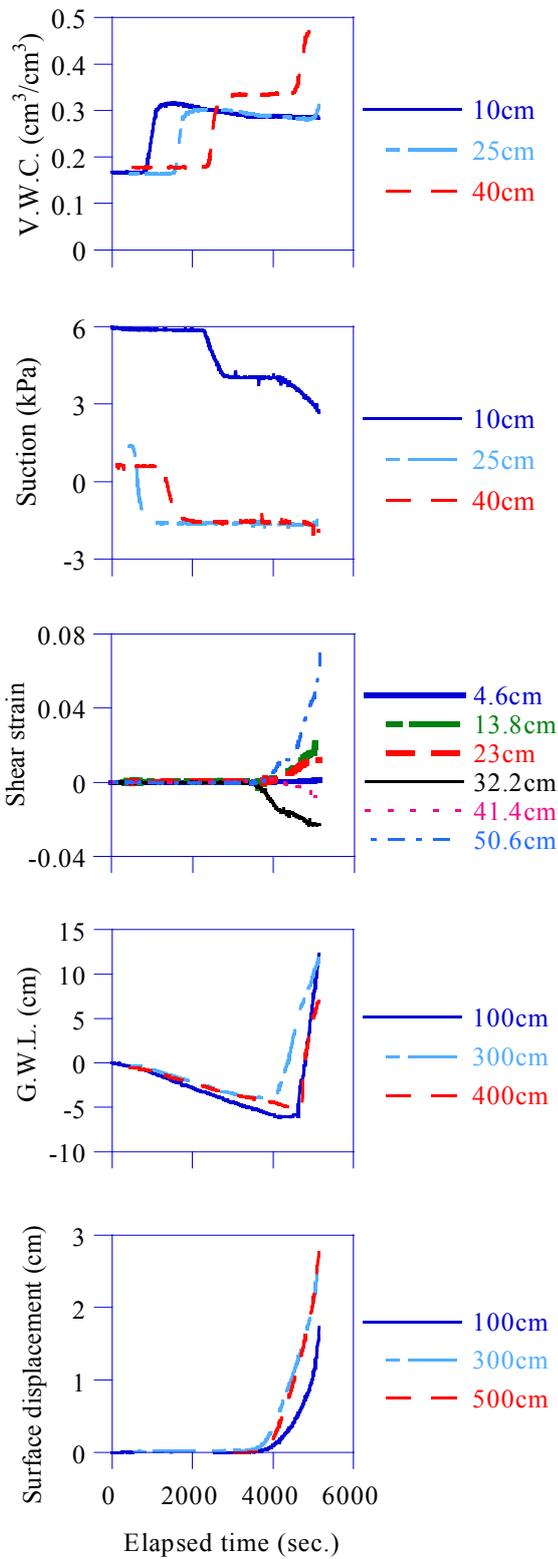
Fig.5 Time variation of V.W.C., suction, shear strain, pore pressure, and surface displacement (30 deg.)
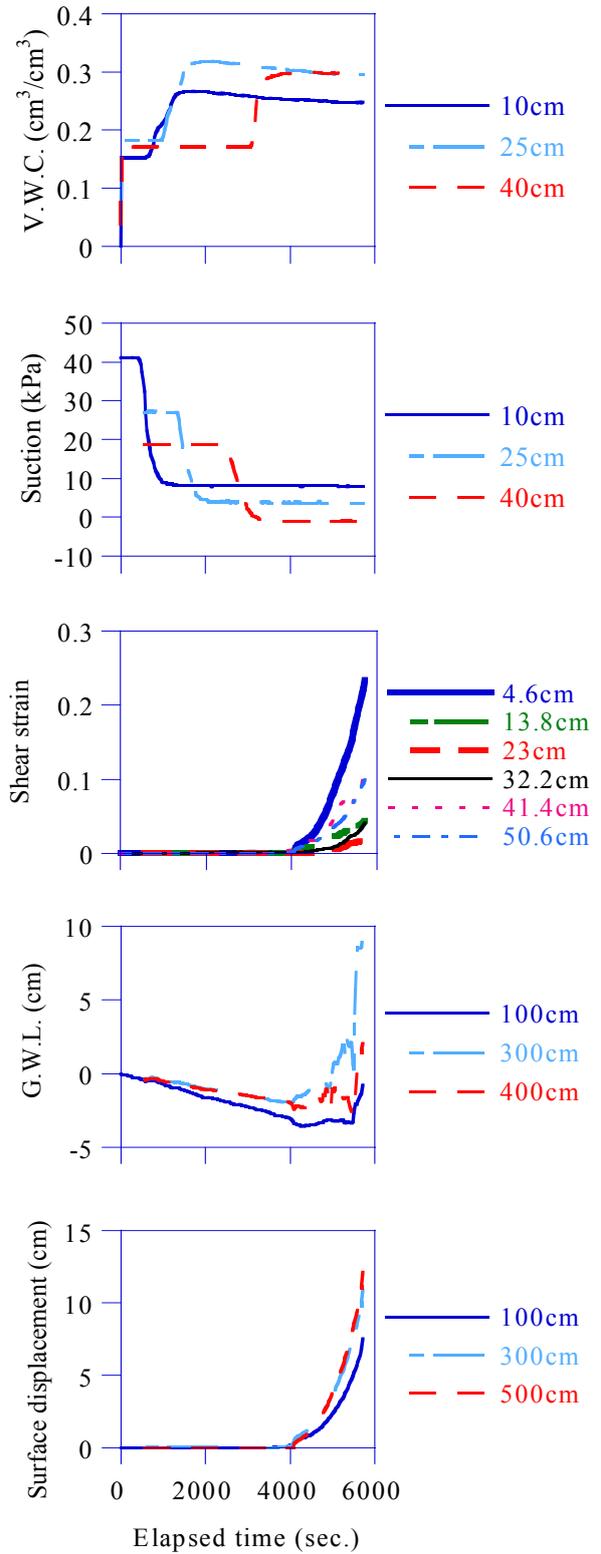
Fig.6 Time variation of V.W.C., suction, shear strain, pore pressure, and surface displacement (40 deg.)

(a) 30deg.

(b) 40deg.
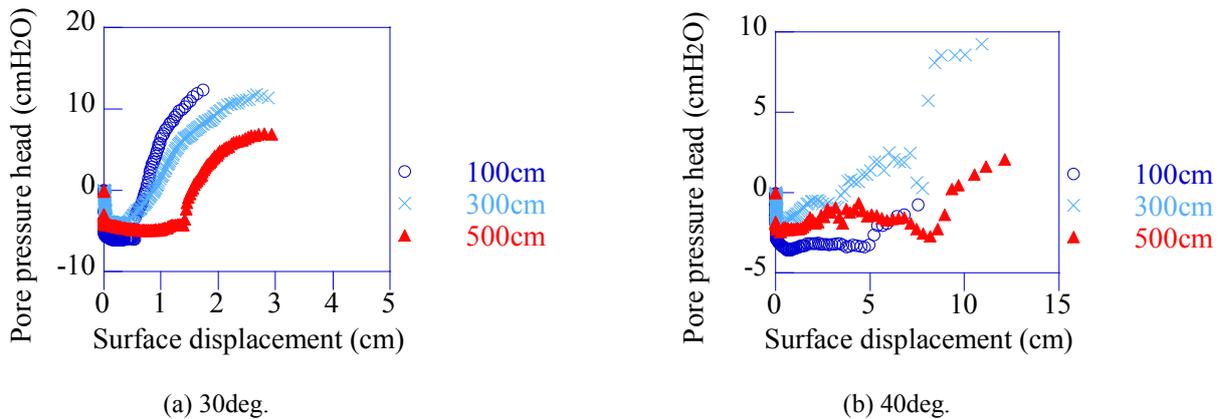
Fig.7 Relation between surface displacement and pore pressure
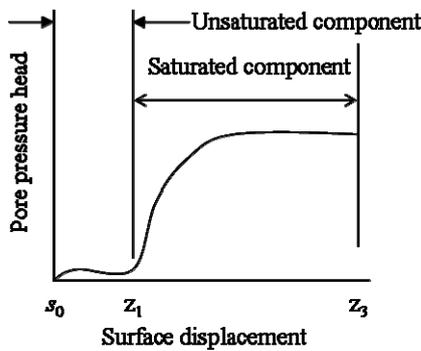
Fig.8 Definition of saturated and unsaturated component of surface displacement
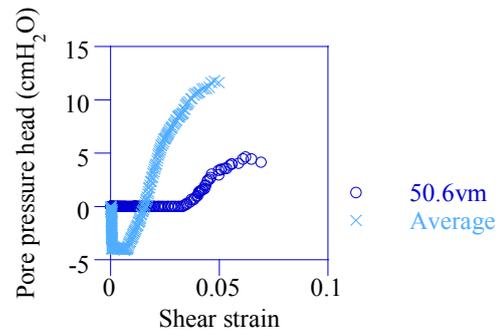
Fig.9 Relation between shear strain and pore pressure

almost same with those of 300cm, 500cm. This fact suggests that shear deformation and groundwater rise at any cross-section from 100cm to 500cm is almost same. G.W.L. continues slight decrease from the start of the experiment until 4000sec., and then makes remarkable increase after almost 4000sec.. Surface displacement also makes no increase until 4000sec., then increases rapidly. Surface displacement and shear strain in the slope make remarkable increase after around 4000sec when G.W.L. starts rise. It suggests that shear deformation proceeds according to increase of pore pressure in the slope of 30deg..

Fig.6 shows time variation of V.W.C., suction and shear strain in the slope at 300cm from the toe of the slope, G.W.L. and surface displacement at 100cm, 300cm, 500cm from the toe of the model slope with 40deg inclination. V.W.C. starts increasing earlier at shallower depth, then keeps almost constant vale within 0.25~0.3. Suction also starts decreasing earlier at shallower depth, then keeps almost constant value within 0~10 kPa. Shear strain makes little variation until 4000sec., then remarkably increases to positive. G.W.L. keeps negative and continues slight decrease until 4000sec., then increase largely. G.W.L. at 100cm, 500cm is lower than

that at 300cm. Surface displacement also shows almost no variation until 4000sec., then rapidly increases. Remarkable increase of shear strain and surface displacement starts around 4000sec. when G.W.L. starts rise also in the case of the model slope of 40deg.. It suggests that shear deformation in the slope of 40deg. is also greatly influenced by generation of pore pressure.

4. DISCUSSION

4.1 Shear deformation and pore pressure

Fig.7(a) shows the relation between surface displacement and pore pressure head on the base at 100, 300, 500cm from the toe of the slope of 30deg.. Pore pressure head at the base is equal to G.W.L.. Pore pressure head decreases and then keeps -7~-3 cmH2O just after the start of the experiment. Surface displacement increases under unsaturated condition with negative pore pressure at this stage. After the surface displacement of 0.5~1.4cm, it increases with the increase of pore pressure head. Surface displacement increment becomes larger as pore pressure head increases. So the relation

(a) 30deg.

(b) 40deg.
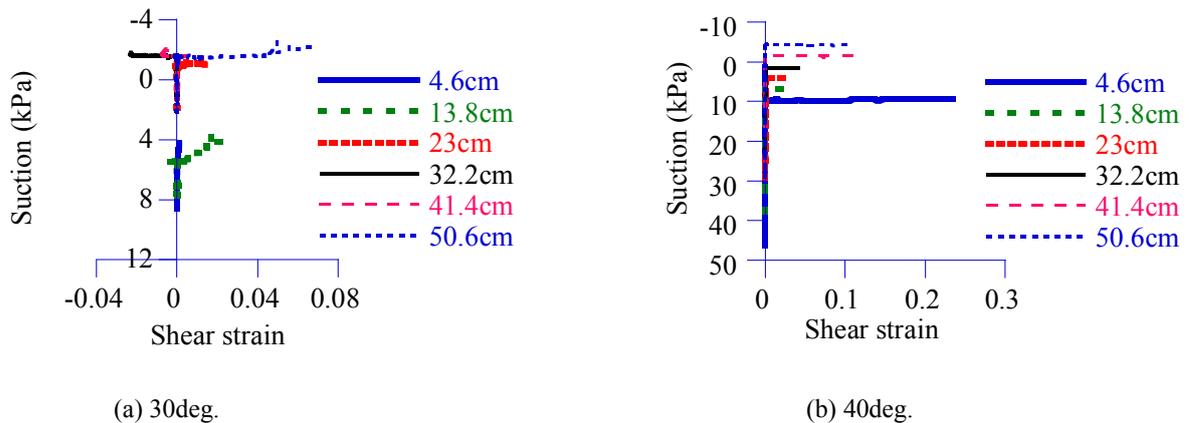
Fig.10 Relation between shear strain and suction

between surface displacement and pore pressure head can be modified by hyperbolic curve which is often adopted for stress-strain relation of the element of soil. The unsaturated component and all surface displacement (Fig.8) are 0.5 and 1.7cm for 100cm, 0.4 and 2.8cm for 300cm, 1.4cm and 2.9cm for 500cm. So the ratios of unsaturated component to all surface displacement are 0.29 for 100cm, 0.14 for 300cm, and 0.48 for 500cm in the slope of 30deg..

Fig.7(b) shows the relation between surface displacement and pore pressure head on the base at 100, 300, 500cm from the toe of the slope of 40deg.. Similar to the relation of the slope of 30deg., pore pressure sudden decreases just after the experiment and keeps -4~0 cmH$_2$O until surface displacement of 5~8cm. Surface displacement proceeds under unsaturated condition in this stage. Although pore pressure of 300cm fluctuates and rises up to 2cm in this stage, it can be thought negative. Fluctuation of pore pressure may be due to error of measurement. Surface displacement remarkably increases with increase of pore pressure after that. Even though pore pressure at the start of this stage of 100, 500cm is negative, this stage can be thought to be under generation of positive pore pressure. Negative value of pore pressure of -4~0 kPa might mean quasi-saturated condition near the base of the slope. The unsaturated component and all surface displacement are 5 and 7.9cm for 100cm, 7.8 and 10.9cm for 300cm, 8.2cm and 12.2cm for 500cm. So the ratios of unsaturated component to all surface displacement are 0.63 for 100cm, 0.72 for 300cm, and 0.8 for 500cm in the slope of 40deg.. The ratio of unsaturated component is larger in the slope of 40deg. than that of 30deg..

Fig.9 shows the relation between shear strain at 50.6cm and pore pressure. For the comparison, relation between average shear strain at the section and pore pressure at the base is also shown. Pore pressure at 50.6cm is defined as the difference between pore pressure at the base measured by groundwater level gauge and vertical distance between the depth of 50.6cm and the base of the slope. Average shear strain is defined as

'surface displacement / soil layer depth (57.7cm)'. Because pore pressure is measured only at the depth of 50.6cm in the slope of 30deg. and it is never measured in the slope of 40deg., the relation between shear strain and pore pressure can be shown only at 50.6cm in the slope of 30deg.. Shear strain at 50.6cm and average shear strain also show increase under unsaturated condition at first, then increase with the rise of pore pressure. The relation between shear strain and pore pressure is also hyperbolic. The difference between shear strain at 50.6cm and average shear strain is the ratio of unsaturated component to all shear strain. The unsaturated component of shear strain at 50.6cm is 0.035 and all shear strain is 0.07, so that the ratio of unsaturated component is 0.5. While the ratio of unsaturated component of average shear strain is just same with that of surface displacement at 300cm of 30deg., so the ratio is 0.14. The ratio of shear strain at 50.6cm is much larger than average shear strain at the section.

4.2 Suction and shear strain in the slope

Fig.10(a) shows the relation between suction and shear strain at the same depth in the slope of 30deg.. Suction decreases with small increase of shear strain in the soil layer shallower than 23cm. Especially shear strain at 4.6cm is almost zero even after the increase of suction up to 4 kPa. Suction is still positive after the decrease at those depths. At the depth shallower than 23cm, shear strain continues to be almost zero with the increase of suction up to -4~0 kPa of suction, then it proceeds under almost constant suction. Shear strain proceeds to positive at 23, 50.6cm while it proceeds to negative at 32.2, 41.4cm with positive constant suction..

Fig.10(b) shows the relation between suction and shear strain at the same depth in the slope of 40deg.. Shear strain keeps almost zero with the increase of suction at first, then proceeds with almost constant suction at all depths. Shear strain increases under positive suction (unsaturated condition) in the soil layer shallower than 32.2cm while it increases under

(a) 30deg.
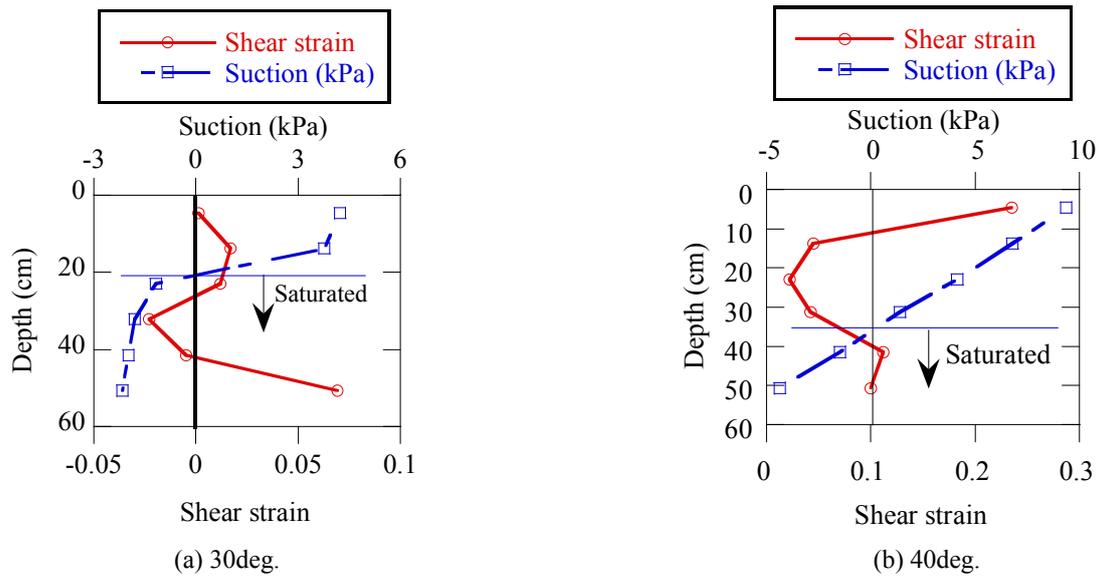
(b) 40deg.

Fig.11 Vertical profile of shear strain just before failure
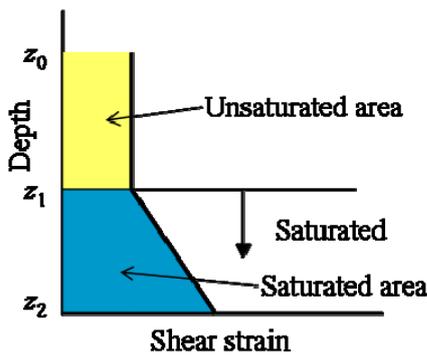
Fig.12 Definition of unsaturated and saturated area

negative suction at 41.4, 50.6cm. Shear deformation proceeds at unsaturated condition at deeper soil layer in the slope of 40deg. than that of 30deg..

Fig.11(a) shows the vertical profile of shear strain and suction at 300cm from the toe of the slope of 30deg.. Soil layer with negative suction is assumed to be saturated. Shear strain at deeper soil layer is larger than that near surface. Shear strain at 23~41.4cm depth is negative which might mean inverse movement of tilt meter at the depth corresponding to large movement of upper or lower tilt meter. Deeper soil layer is saturated. In the slope of 30deg., shear strain increases largely at saturated soil layer. Fig.11(b) shows the vertical profile of shear strain and suction at 300cm from the toe of the slope of 40deg.. Shear strain is larger near surface where suction is positive, while it is relatively smaller near the base which is saturated. In the slope of 40deg., shear strain increases largely at unsaturated soil layer.

4.4 Shear deformation under different slope inclination

According to the examination as above, shear deformation at saturated layer is larger in the gentler slope while shear deformation at unsaturated layer is larger in steeper slope. In order to compare the contribution of unsaturated component to shear deformation at examined section of the slope under different slope inclination, ratio of unsaturated part of shear area under different slope inclination is calculated from Fig.11. Shear area is defined as sum of shear strain from one depth to other depth, and is derived by the equation below.

$$A = \int_{za}^{zb} \gamma dz \tag{1}$$

Here, A: shear area, γ: shear strain at some depth, za, zb: depth ($za<zb$). Shear area under unsaturated layer and saturated area in each slope is illustrated at fig.12. The ratio of shear area of unsaturated layer are 0.17 for the slope of 30deg. while it is 0.58 for 40deg.. So contribution of shear deformation at unsaturated layer is larger in the steeper slope. It is same trend with the ratio of unsaturated component of surface displacement that is larger in the steeper slope.

On the other hand, contribution of shear deformation at saturated layer with the increase of pore pressure is larger in the gentler slope. Fig.9 shows that the ratio of unsaturated component to all shear strain at 50.6cm is larger than the ratio for average shear strain at the section. The reason of this difference might be suggested from Fig.8(a) as below. Shear strain at deeper layer than 50.6cm might be larger than that at 50.6cm, and be dominant for shear deformation at the section in the slope of 30deg.. And it is generated under saturated condition. Shear deformation at deeper depth under saturated condition might be larger and dominant in the slope of 30deg..

It might make the ratio of saturated component to shear deformation at the section become larger than that at 50.6cm.

5. CONCLUSION

From the examination as above, the facts as bellows are made clear.

(1) Surface displacement and shear strain in the slope make remarkable increase at the time of rise of G.W.L.

(2) Surface displacement proceeds at unsaturated condition at first, then increases remarkably with the increase of pore pressure at the base. The relation between surface displacement and pore pressure is hyperbolic just like stress-strain curve of soil element. The relation between shear strain and pore pressure also has same characteristics. The ratio of unsaturated component to all surface displacement is larger in steeper slope.

(3) In the slope, shear strain proceeds under almost constant suction after rapid increase of suction. Unsaturated soil layer near surface is thicker in the steeper slope.

(4) Shear strain at saturated zone near bottom is larger than that at unsaturated layer in the slope of 30deg., while shear strain at unsaturated layer near surface is larger in the slope of 40deg..

(5) Contribution of unsaturated shear deformation is larger in steeper slope while the role of shear deformation at saturated layer is larger in the gentler slope.

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