IN-SITU MEASUREMENT OF INTERNAL EARTH PRESSURE DURING LANDSLIDE MOVEMENT

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ABSTRACT

Lateral internal earth pressure during landslide movement was observed in-situ at two-minute intervals. The data obtained are discussed together with other observational data for the landslide. Findings for actual landslide motion in three distinct events are summarized as follows: variation in the observed earth pressure differed with the borehole position. Variation at the onset of movement was measured in a limited number of boreholes. Large variation appeared after a certain amount of relative displacement occurred at the slip surface. There was a rapid increase in earth pressure in almost all the boreholes at the moment movement stopped. Anisotropic stresses in earth pressure that accumulated during movement were released when it stopped, and the difference in pressure before and after the sliding was small. An almost constant peak earth pressure, designated the passive earth pressure, was found in a borehole during the three events.

Key words: earth pressure, effective stress, field test, landslide, slip surface, water pressure (IGC: C7)

INTRODUCTION

Since Coulomb first established his theory of earth pressure, there have been many studies of the theoretical and practical aspects of pressure acting on a retaining wall. Pressures acting on stabilization piles and water catchment wells have been investigated (e.g., Fukumoto, 1972) in relation to landslide prevention works. Researchers have focused on the force acting on a rigid structure because their main interests have been concentrated on design problems. The pressure inside a sliding soil mass, however, has received little attention.

Measurements of the internal earth pressure during soil movement have been made in the laboratory (e.g., Fukuoka et al., 1985) but, mainly because of technical difficulties, few attempts have been made to measure in-situ pressure. Hada et al. (1988) used an especially designed transducer to measure the static internal earth pressure in a landslide and reported that the observed pressure was appreciably smaller than the value calculated by the slice method. Recently, rupture of a soil mass has come to be considered progressive failure, whereas the conventional theory of earth pressure is based on static equilibrium assuming simultaneous mobilization of peak resistance in the whole sliding soil mass. To investigate the dynamic property of earth pressure during rupture, it must be measured as time-variant

data. Fukuzono (1993), who made dynamic measurements of stresses in large-scale laboratory tests, obtained interesting results, only some of which agree with results obtained by the conventional theory.

We have measured the dynamic variation in lateral internal earth pressure during the movement of a soil mass in an active landslide for which other monitoring data were available. Our findings show the dynamic character of rupture in the scale of the actual landslide and provide information for designing landslide prevention work.

TEST SITE

The test site is the Nishi-Ikawa landslide in the Sanbagawa metamorphic rock region of Shikoku Island, southwest Japan (Fig. 1). The landslide is close to the Median Tectonic Line (MTL), one of the major active fault systems in Japan. Figure 2 shows the geological setting around the landslide (after Mizuno et al., 1993), "landslide" being identified morphologically (not geotechnically). An ancient landslide scarp can be seen uphill of the present landslide. The crown of the scarp has been partially dissected. The present landslide took place in the deposit of the ancient one, but there was no sign of landslide activity before 1973 when an artificial cutting at the toe made the landslide active. Since 1973, sliding has occurred repeatedly at times of heavy rainfall. The recent

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Fig. 1. Location of the Nishi-Ikawa Landslide in Japan

Fig. 2. Geological setting around the Nishi-Ikawa Landslide (after Mizuno et al., 1993)

average rate of displacement is several centimeters per year, and the average annual precipitation in this region is 1401 mm. Figure 3 shows the topography and arrangement of the monitoring equipment.

The sliding mass consists of soils of weathered rocks comprised of argillaceous and green schist. The P-wave velocity structure in this landslide was determined by Maeda and Shima (1982) who used a refraction seismic survey; the surface layer of $V_p = 370 \sim 450$ (m/s) is from 2–10 m deep, the second layer of $V_p = 1200 \sim 1500$ (m/s) from 20–25 m deep and the basement of 3200 (m/s) below that. Suemine (1983) monitored the landslide in detail. He maintained the slide to be a progressive failure and estimated the propagation speed along the slip surface to be of the order of 10 (m/hour). Figure 4 shows two cross sections of the survey lines in November 1995. The head scarp of the present landslide is located at exten-

Fig. 3. Topography of the Nishi-Ikawa Landslide and arrangement of the monitoring equipment (BV: borehole vertical for observation, EX: extensometer)

Fig. 4. Two cross sections of the survey lines

someter No. 1 in Figs. 3 and 4. The depth of the slip surface at each borehole was identified by the use of strain gauges attached to pipes embedded in the landslide area (as discussed later) and checked by measurements made on an insertion-type bending-pipe (Shima and Takeuchi, 1973).

OBSERVATION

Earth pressure transducers were installed in six boreholes (BV 4 through 9 in Fig. 3). Internal earth pressures, pore pressures at the slip surface, and pipe strains were measured using these boreholes. Figure 5 shows the scheme for an observation borehole. Earth pressure transducers and strain gauges (omitted in Fig. 5 for the sake of

Fig. 5. Schematic structure of an observation borehole

clarity) were attached to the outer surface of a pipe (an unplasticized polyvinyl chloride (PVC) pipe with an outer diameter of 48 mm and wall thickness of 3.6 mm) embedded in the borehole (diameter 142 mm). After insertion, the clearance between the pipe and the original soil was carefully filled with sand to obtain uniform back-filling. Table 1 shows the installation depths of the earth pressure transducers. Two transducers were attached at each depth; one facing in the direction of the maximum slope gradient, the other perpendicular to the first transducer. We here use "UD" for the direction of the first transducer and "RL" for the second. A positive value indicates compression.

Pairs of strain gauges were bonded to the surface of a PVC pipe at various depths in order to measure the distribution of the bending strain. At each depth, there were two gauges; one on the up-slope side, the other on the down-slope side to compensate for the effect of variations in temperature (two-gauge method). The distance between the neighboring pairs was 0.33 m at the depth of the slip surface in order to measure the strain distribution near the surface precisely, and the distance was 1 m at depths distant from the surface. Results of a calibration test of strain measurement made in the laboratory are shown in Fig. 6. A pipe with a pair of strain gauges was bent, and its output (X ($\mu\epsilon$: 10^{-6} strain)) plotted against the curvature (R (m)) of the pipe. The relative displacement (Y (m)) of the end of the pipe obtained geometrical-ly using R is

$$Y = l^2 / R$$

where l is the length of the pipe and $1/R$ is assumed to be

Table 1. Installation depths of the earth pressure transducers and the soil properties there

BV	Transducer depth (m)	Distance from slip surface (m)	Soil properties (color*)
BV 4	3.25	+7.5	loose sandy (y/br)
	8.25	+2.5	stiff silty (br)
	13.25	-2.5	loose sandy (y/gy)
	18.25	-7.5	clayey (bl)
BV 5	0.75	+7.4	loose sandy (y/br)
	5.75	+2.4	loose silty (gy)
	10.75	-2.6	loose silty (y/br)
	14.75	-7.6	stiff silty (gy)
BV 6	0.75	+1.2	loose silty (y/gr)
	4.25	-2.3	stiff sandy (gr)
	9.25	-7.3	stiff clayey (gy)
BV 7	6.25	+2.0	loose silty (y/br)
	11.25	-3.0	clayey (gr)
BV 8	12.25	+3.3	stiff silty (y/gy)
	17.25	-1.7	stiff clayey (y/gy)
BV 9	4.25	-1.7	loose sandy (y/br)

* Soil color was checked during boring.

y; yellow, br; brown, gy; gray, bl; black, gr; green.

Transducers at the underlined depth are used in discussion.

Fig. 6. Calibration test results for measurement of the strain on a pipe

sufficiently small.

The relationship between the outputs of strain gauge and the relative displacement is shown in Fig. 7 for $l=0.33$ m, the same value as that for the system used in the field. This relationship was obtained assuming that pipe strain is uniform (the radius of the curvature is constant) for 0.33 m long. Though the assumption, to be exact, may not be valid near the slip surface in a real landslide, we used it as an approximation. Both positive (for a strain gauge above the slip surface) and negative (for one below it) strains are observed in our measurement.

Fig. 7. Relationship between the output of the strain gauge and the relative displacement, calculated from Fig. 6

To calculate relative displacement of the sliding soil mass and basement, the sum of absolute values of strains measured at two depths, just above and below the slip surface, must be used as X in the relationship.

Movement of a landslide is generally governed by the pore pressure acting on its slip surface, which must be measured when the mechanism of the landslide is investigated. It is necessary to isolate the existing pore water in the soil near the slip surface from that at other depths in order to measure the pressure acting on the surface. We placed two bentonite layers (Fig. 5) in the back-fill sand (0.5 m above and below the slip surface) to satisfy this requirement. There are drainage holes on the PVC pipe at the depth of the slip surface through which pore water flows into/out of the pipe. The pressure is balanced by the head height of the water inside the pipe. Pore water pressure at the slip surface therefore can be measured by a hydro-pressure transducer placed inside the pipe. The absolute value of the transducer is reliable because it is calibrated every few months.

Outputs of the earth pressure transducers and strain gauges are sampled digitally at two-minute intervals. Data from the pore pressure transducers are recorded by multi-scanning pen-recorders (chart speed = 25 mm/hr) in the field then digitized manually at thirty-minute intervals in the laboratory. The above monitoring equipment was positioned in June 1994 for BV 7 to 9 and in June 1995 for BV 4 to 6. The zero balances of earth pressure transducers may drift during installation, but there is no way to calibrate them after installation. We will therefore discuss the variations in each sensor on the basis of the initial values obtained in the data-acquisition period.

EARTH PRESSURE MEASUREMENT

Measurement of earth pressure is very difficult because

many factors may affect it (e.g., see Hariu, 1984). Brackley and Sanders (1992) made in-situ measurements of the lateral internal earth pressure in a flat land composed of expansive clay. They made in-situ tests to check the validity of their measurements and obtained acceptable results, showing that it is possible to measure in-situ earth pressure accurately when there is careful instrumentation and favorable field conditions (flatness, fine material, uniform geology).

Our purpose was to measure pressure at various depths and in many boreholes to determine the earth pressure both at one point and its distribution within an actual landslide; therefore, it was impossible to have careful instrumentation like that of Brackley and Sanders. Consequently, our instrumentation is less accurate. In the installation procedure described, there are three questionable factors: 1) the soil in contact with the surface of the transducer is sand, 2) the transducer is attached to the PVC pipe which may be strained by changes in stress in the surrounding soil, and 3) the stress field may have been disturbed by the boring and back-filling.

Factor 1 may cause stress concentration and eccentric loading on a transducer. Such effects can be decreased by the use of fine sand in the back-filling and the choice of a well-designed transducer.

The effect of Factor 2 was tested by changing the pressure *inside* the pipe. When the water pressure inside the pipe was increased by poring in water from 0 to 78.4 kPa, the outputs of the earth pressure transducers did not change. Strain on the pipe caused by change in the inner stress in this range is not so large to disturb the measurement of earth pressure. This is not direct evidence that the effect of Factor 2 may be ignored when the pipe is strained by change in the *outside* stress, but it favors our assumption.

Another problem is whether the pipe at the depth of the transducer is strained by relative movement at the slip surface. Figure 8 shows the difference of maximum and minimum values in outputs of all strain gauges during Event 1 plotted against the distance from the slip surface. It is clear that strain along a pipe attenuates rapidly with the distance, becoming negligible at the distance of 0.8 m in this landslide. This result agrees with analytical results obtained by Nakamura and Itagaki (1976) who investigated the behavior of PVC pipes in the ground using Chang's equation, and showed that bending strain and moment are negligible at a point 1 m distant from the slip surface. Because earth pressure transducers are attached at least 1.2 m distant from the slip surface, the pipe at that depth is hardly strained by relative displacement at the slip surface. Therefore, we can assume that the earth pressure measurement is not disturbed by the bend of pipe. This assumption is also supported by measurements showing that the difference in effective earth pressure before and after sliding is small (see later section), because any disturbance which can be caused by the bend of pipe is considered irreversible.

Factor 3 indicates a fundamental problem in measuring "natural" internal earth pressure. This problem can

Fig. 8. Attenuation of maximum variation of pipe strain with the distance from the slip surface

not be solved without using “remote sensing”, for which the appropriate technology does not exist at present. We tried to decrease this effect by having the installation in boreholes instead of in excavated pits.

The structure of the earth pressure transducer used is shown in Fig. 9. This transducer was chosen because its output is not much disturbed by eccentric loading on the first diaphragm, it has high water resistance with good linearity, and its size is suitable for installation in a borehole; all qualities necessary to the measurement of internal earth pressure at many depths and points. On the

Fig. 9. Structure of the earth pressure transducer used (unit: mm)

other hand, the diameter dimension and aspect ratio (height/diameter) are sacrificed. A large diameter and small aspect ratio are considered preferable for accuracy; but, in practice, it is difficult to fulfill both these properties as well as the conditions given above.

DATA OBTAINED

The three movement events observed since the first installation of the earth pressure transducers were designated Events 1, 2, and 3 in terms of the amount of displacement of the sliding mass observed at BV 7. Figure 10 shows the results of strain measurement on the pipe at BV 7 at depths just above and below the slip surface for each of the three events. The time origin is the moment of onset of data acquisition for each event. Displacement shown in the figure is calculated using the relationship in Fig. 7. Events 2 and 3 occurred before the installations of BV 4 to 6 and Event 1 occurred about one month after their installations. All the events occurred between May and July 1995, almost one year after the installations of BV 7 to 9. We will discuss the variation in each output during this period.

The earth pressures measured in BV 4 during Event 1 are shown in Fig. 11 as an example of the recorded data. These pressures were calculated using the initial imbalance of each transducer as measured in the laboratory before field-installation in order to show the stability of the zero balance of the transducer. As stated, the zero balance of an earth pressure transducer may drift during installation. There is a marked difference between the values observed for 13.25 m UD and RL, but the variation is very similar. We consider that this difference was caused by the drift of the zero balance of one (or both) transducer(s) during installation. The values measured at

Fig. 10. Strain measurements for the pipe at BV 7 at the nearest depths above and below the slip surface for three events

Fig. 11. Earth pressure in BV 4 (upper 4 diagrams) and pipe strain at the slip surface in BV 4 (bottom diagram) during Event 1

Fig. 12. Pore water pressures at the slip surface during Event 1 and hourly precipitation

Fig. 13. Calculated highest and lowest level of ground water during Event 1

the depth of 18.25 m (both directions) are very low and their variations are small. There are two possible causes for them; the “earth pressure coefficient” (horizontal earth pressure/vertical one) is small because of stiffness of the ground at that depth, and the absence of ground water, but an error of measurement caused by arching effect is also possible in stiff ground.

Figure 12 shows the pore water pressure at the slip surface depth measured at BV 4 to 9 during Event 1. We calculated the pore water pressures at the depth of each earth pressure transducer from this value on the assumption that ground water is present as free water. The assumption is made because the sliding soil mass is composed mainly of loose sandy material, which is considered permeable. Figure 13 shows the calculated highest and lowest level of ground water during Event 1. Ponds could be seen around BV 5 after Event 1 and the highest level is almost the same as the ground surface there. We consider that our assumption is acceptable. We could obtain effective earth pressures by subtracting the calculated pore pressures from the measured earth pressures.

Figure 14 shows variations in calculated effective earth pressure and measured pore pressure at the slip surface in BV 4 during Event 1. There is marked variation in 3.25 m RL compared to UD direction. Small variations are generally observed for transducers at shallow depths in this landslide but this transducer (3.25 m RL in BV 4) is an exception; the reason for this is not yet clear. A rapid increase in pressures is seen at 8.25 m, while a decrease is seen at 13.25 m. Calculated effective earth pressures for 18.25 m are almost the reverse of the pore pressure at the slip surface because observed earth pressures have slight variations as shown in Fig. 11. It is not clear whether this result is correct or is caused by an error in earth pressure measurements.

Fig. 14. Effective earth pressure (upper 4 diagrams) and pore water pressure at the slip surface in BV 4 (bottom diagram) during Event 1

DISCUSSION

As shown in Fig. 14, variations in the effective earth pressure above and below the slip surface are opposite to each other in BV 4. This result was also obtained in BV 7, but not in BV 5 and 8. Figure 15 shows their variations in BV 5. The effective earth pressure in UD direction at 5.75 m shows a sudden drop at the beginning and a jump at the end, while the pressure at 10.75 m shows a gradual decrease followed by a jump. A similar result was observed in BV 8. Variations in the effective earth pressure above and below the slip surface are not opposite to each other in these two boreholes (BV 5 and 8). Their tendencies (decrease in pressure) are the same but their rates are different. Effective earth pressures below the slip surface decrease in all boreholes although their rates are different depending on position (high in BV 4 and 7 and low in BV 5 and 8). We consider that this is due to a reduction of the driving force towards the down slope in the basement, because resistance stress decreased at the slip surface due to a decrease in effective stress. On the other hand, effective earth pressures in the sliding soil mass

Fig. 15. Observed and effective earth pressures in the UD direction (upper 2 diagrams) and pore water pressure at the slip surface in BV 5 (bottom diagram) during Event 1

vary depending on position.

The variation in the effective earth pressure above the slip surface is smaller than that below the surface in BV 5, but the former is larger than the latter in other boreholes. To discuss dynamic variation in the internal earth pressures of a sliding soil mass, we use the outputs of the earth pressure transducers installed at the nearest depth above the slip surface in each borehole (underlined transducers in Table. 1). Hereafter, their depths are not mentioned.

Comparison of Earth Pressures in Boreholes at Various Points in the Landslide

Figure 16 shows variations in the effective earth pressure in the UD direction in each borehole during Event 1. As an index of displacement of the soil mass, the pipe strain at slip surface in BV 7 is also shown (bottom). In BV 4 and 7 there was a rapid increase in pressure at the beginning, then a gradual decrease while the soil mass was moving, followed by another increase at the end of movement. BV 5 and 8 show a sudden drop in pressure at the beginning and a jump at the end. On the basis of these earth pressure measurements, the soils around BV 4 and 7 appear to have been compressed ("passive" mode), while those around BV 5 and 8 expanded ("active" mode). BV 4 and 7 are uphill respectively of BV 5 and 8. The measurements indicate that the soil in the passive mode was uphill of that in the active mode, which is the reverse of the situation in ideal slope failures (uniform soil character, theoretical distribution of ground water, and simple-shaped slip surface). The distribution of the deformation mode is governed both by the shape of the slip surface and the distribution of friction along that sur-

Fig. 16. Variations in the effective earth pressure in the UD direction at the nearest depth above the slip surface in each borehole during Event 1 (upper five diagrams) and pipe strain at the slip surface in BV 7 (bottom diagram)

face in a landslide with a well-developed slip surface. Relatively high pore pressures were present in BV 5 and 8 as shown in Fig. 12. These two boreholes show decreasing type variations in earth pressure (Fig. 16) at the beginning of the soil mass's movement, whereas BV 4 and 7 show increasing type variations. We consider that the observed difference in earth pressure variations is caused by the pore pressure distribution on the slip surface (therefore by the ratio of the friction force at the slip surface to the driving force caused by the weight of soil column above this surface). Unfortunately, our measurements are limited in the middle to the lower part of the landslide. The passive soil deformation mode around BV 4 and 7 must have been due to another active soil uphill.

BV 6 in Fig. 16 shows a slight tendency towards compression. We can not tell about BV 9 because there is no transducer above the slip surface. The variation in earth pressure at the toe, however, was relatively small compared to the variations in uphill boreholes (earth pressure below the surface at BV 9 also shows slight variation).

The effective earth pressure varies markedly depending on position, indicating that the sliding soil mass did not move as one body. The mechanism of a soil mass's movement with a well-developed slip surface is explained as the slip of an elastic body on the surface rather than failure of the entire mass. Soil around the slip surface is

in, or very near to, a plastic state, whereas other parts of the sliding soil mass remain elastic (as Vermeer (1990) pointed out in his theoretical analysis of biaxial tests). If displacement was uniform along the slip surface, there would be no strain *inside* a sliding mass, whereas there must be shear strain *between* the sliding mass and the stable base-ment), so there would be no earth pressure change. We, however, found variations in the effective earth pressure, indicating that displacement along the slip surface was not uniform, thereby causing strain inside the sliding mass during its movement.

Onset of Rupture

Earth pressure variations in the UD direction at about the onset of landslide movement are shown in Fig. 17. The pipe strain near the slip surface at BV 7 (bottom of the diagram) indicates that the relative displacement at the slip surface began at a time between 10 to 10.5 (hours) at BV 7. There is no variation in the earth pressure in BV 4 or 7 before that, whereas BV 6 and 8 show similar variations at that time, and BV 5 shows a slight variation. Although small, we consider these precursory variations (BV 5, 6, and 8) to be physically associated with the onset of rupture because they occurred at differ-

Fig. 17. Variations in the effective earth pressure in the UD direction at the nearest depth above the slip surface at the onset of landslide movement (upper five diagrams) and pipe strain at the slip surface in BV 7 (bottom diagram) during Event 1

ent depths and boreholes at the same time. The first onset of rupture appears to have been a relatively small event in terms of earth pressure, which might be the result of its being local (rupture did not occur along the entire slip surface at once).

The earth pressures in BV 5 and 8 showed “active” variations, as stated, and the rupture phase was detected in these two boreholes, indicative that the soils around these two boreholes were liable to rupture. In contrast, the soils around BV 4 and 7, at which points the earth pressures showed “passive” variations and no rupture phase was detected, behaved as a “barrier”. This interpretation agrees with the speculation that stress in the soils around BV 5 and 8 at the slip surface were close to failure condition because the pore pressures at the slip surface were high in these boreholes.

Large variations in earth pressure first appeared after a considerable amount of displacement of the sliding mass. Figure 18 shows the relationship between the effective earth pressure and relative displacement between the basement and sliding mass in each borehole. Variation in the effective earth pressure appears at about 10^{-2} (cm), displacement apparently preceding stress. The rupture of the limited area then propagated along the slip surface. The soil mass above the surface lost uniformity, thereby inducing larger variation in the effective earth pressure.

The End of Movement

As pore pressures dissipated after rainfall stopped, the

Fig. 18. Relationship between the relative displacement at the slip surface and the effective earth pressure at the nearest depth above the slip surface during Event 1

rate of pipe strain decreased. In this stage, the effective earth pressures increased in all the boreholes, but variations in those located in the foot of the landslide were relatively small (BV 6). Figure 19 shows the phenomena observed during Event 1. The increase first appears at BV 8 (in every event), “hesitant” behavior being seen before it. In BV 6, the increase is slight. As seen in Fig. 16, the effective earth pressure returns to almost the same level as that before sliding in BV 5 and 8 at this time. The pressure in BV 7 is still higher than the initial value at the end of the period in Fig. 16 (150 (hours)), but it gradually decreases becoming almost the initial value at about 300 (hours). The difference in the stress condition before and after movement is small, which would facilitate the repetition of movement. The rate of the effective earth pressure increase in the stopping phase is high compared to the rate of pore pressure dissipation at that time (pore pressure at the slip surface in BV 7 is shown at the bottom of Fig. 19). This indicates that the shear resistance along the slip surface recovered rapidly when a particular kinematic condition was reached. The end of landslide movement can be indicated by the rapid increase in the effective earth pressure, whereas it is not clearly detected by pipe strain (see Fig. 16).

Fig. 19. Variation in the effective earth pressure in the UD direction at the nearest depth above the slip surface at the end of landslide movement (upper five diagrams) and pore water pressure at the slip surface in BV 7 (bottom diagram) during Event 1

Comparison of Earth Pressure in the UD and RL Directions

As stated, the rupture phase was observed in some boreholes, whereas the stopping phase was seen in almost all of them. This difference may have been caused as follows;

Figure 20 shows the difference between the observed variations in the UD and RL directions. By examining these data, we can eliminate the effect of pore pressure without making any assumption about it, and their comparison is possible. Clearly, there is a marked difference during motion, which becomes small after the stopping phase. The values in BV 4 and 7 are small at the beginning of motion and increase up to the stopping phase. Although we can not make a detailed discussion about the stress condition, because the absolute earth pressure outputs are suspicious and our measurements are limited in two directions, the difference can be seen as an index of the anisotropy of stresses. Figure 20 seems to indicate that anisotropic stress accumulated during movement and was released after the stopping phase. During the movement of the landslide, the internal strain of the sliding soil mass was governed by the distribution of the slip rate as determined by the distribution of the resistance force along the slip surface (and by the boundary conditions). In contrast, before and after movement, the stress inside the ground was determined by the structure of the ground itself.

Fig. 20. Time variation in the difference between earth pressure in the UD and RL directions at the nearest depth above the slip surface during Event 1

Comparison of Events

According to traditional theory, the earth pressure at the moment of the failure of a soil mass is a constant determined by the soil strength and mode of deformation (passive/active). In the "active" region, it may decrease down to the active earth pressure value, whereas in the "passive" region it may increase up to the passive one, both extreme pressures being determined only by the internal friction angle of the soil. This theory is constructed on the assumption of simultaneous mobilization of peak resistance in the sliding soil mass but it is, generally, not valid in real landslides. Two major points are different in real landslides from this assumption; one is the existence of the slip surface and the other is that rupture in a real landslide is progressive. These points may arrest the mobilization of peak stress condition in a sliding soil mass with the result that two extreme pressures can not be observed.

As stated, we succeeded in measuring the earth pressures in BV 7 and 8 during three events. The larger the amount of displacement, the higher the pore pressure at the slip surface. The "effective" earth pressure is used to compare the data obtained for these events. Figure 21 shows the maximum and minimum values and the variation range (difference of those two values) of the effective earth pressure at BV 7 and 8 during movement of the landslide. At BV 7, where the soil was deformed in the passive mode, the maximum value is nearly constant regardless of differences in the amount of displacement (and pore pressure at the slip surface). This value seems to be the *strength* at this point. In other words, the soil around this borehole was under almost constant pressure at failure, which agrees with the traditional theory (the

Fig. 21. Maximum and minimum values and the range of variation in the effective earth pressure at the nearest depth above the slip surface in BV 7 and 8 during the three events (Pore water measurement partially failed in BV 8 during Event 3, therefore neither the maximum nor minimum was obtained, so variation at the beginning of movement is plotted.)

passive earth pressure). There is no such a tendency at BV 8 for either the maximum or minimum value, but there is a positive correlation between the variation range and the amount of pore pressure (and displacement). The active earth pressure was not detected in this borehole, which could be due to the effect of progressive failure, the existence of a well-developed slip surface, or both.

We consider that the fact that the passive earth pressure was observed while the active one was not, is not a fundamental difference. Whether both of them, one of or neither of them is observed depends on the structure of the sliding soil mass. We can state that extreme earth pressures do not always appear in real landslides.

CONCLUSION

In-situ measurements of the lateral internal earth pressure during landslide movement (three events) showed the following: the variation in earth pressure differed from borehole to borehole. Some boreholes showed variations at the onset of movement; others did not. At the end of movement, an increase in earth pressure was observed in all the boreholes. The difference in pressure before and after sliding was small. Anisotropic stress accumulated during movement and was released when it stopped. A comparison of the three events showed that one borehole had an almost constant maximum effective earth pressure (the passive earth pressure) regardless of differences in the amounts of the pore pressure. The active earth pressure, however, was not found in the other boreholes, probably because of the effect of progressive failure, the existence of a well-developed slip surface, or both.

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