RESEARCHES ON RETAININGWALLS DURING EARTHQUAKES

M. Fukuoka (I)
Y. Imamura (II)
Presenting Author: M. Fukuoka

SUMMARY

This paper presents examples of damaged retaining walls by earthquakes and earth pressure measurements with prototype model and real retaining walls during earthquakes. Earthquake movements are not so simple and soils are not so uniform that earth pressures acting cannot be calculated with a simple model. Fluctuations of earth pressure become larger in proportion to accelerations of the ground in a short period. Earth pressures during earthquakes is composed of those in ordinary time and additional pressures. The conventional method, which is based on the Coulomb's formula cannot be applied to estimate earthquake earth pressures.

INTRODUCTION

Earth pressure on retaining walls began to attract the attention of engineers since the Great Kanto Earthquake in 1923. Dr. S. Okabe proposed a method of computing earthquake earth pressure on retaining walls by modifying the Coulomb's formula, because it contained wall friction. Dr. N. Mononobe was interested in this problem too, and made research work from analytical point. Dr. H. Matsuo started to perform model tests under Dr. Okabe. His work was succeeded by Prof. M. Ichihara, Dr. Y. Ishii, Prof. S. O'hara, and et al. Their main concerns were designing earth pressures on quey walls.

Fukuoka began to make research work on retaining walls constructed at mountainous roads. Coulomb and Rankine formulae were used widely in this country. And then charts for estimating pressure on backfill against retaining walls were introduced by the "Soil Mechanics in Engineering Practice" of Professors Terzaghi and Peck. Those formulae are based on assumption that the backfill is under plastic equilibrium, and effect of cohesion is neglected. Fukuoka invented the panel type earth pressure gauge, which measured resultant force of earth pressure decomposing it into normal and tangential components. Generally earth pressures were regarded to vary with only soil types as described in the Terzaghi-Peck's text book. Fukuoka revealed the earth pressure did vary with such factors as method of construction, inclination of wall, flexibility of wall, shape and thickness of backfill, foundation, etc. The panel type earth pressure gauges were connected to a dynamic recorder to get earthquake earth pressure. Multiple anchored retaining wall was constructed, and dynamic forces on anchor rods were recorded during earthquake.

METHOD OF OBTAINING DESIGNING EARTH PRESSURE WIDELY USED

The method obtaining designing earth pressure on retaining walls were proposed by Drs. Mononobe and Okabe in Japan around 1924, which has been

(I) Professor, Science University of Tokyo, Japan

(II) Lecturer, Science University of Tokyo, Japan.

widely used since then. The formula is based on the Coulomb's formula. It contains unit weights and angles of internal friction of backfill materials (neglecting cohesions), and frictional angles between walls and backfills (wall frictions). This method is divided into two. The first one is reducing angle of internal friction by arctan k. and the other is tilting retaining wall system (retaining wall body and backfill) by arctan k. Where, $k=k_h/(1-k_v)$, and k_h and k_v are horizontal and vertical seismic coefficient respectively. Soil constants obtained with ordinary laboratory testings, namely, angle of internal friction, cohesion, Young's modulus and Poisson's ratio are not taken into consideration to estimate earthquake earth pressure similar to the Coulomb's case.

BEHAVIOUR AND RUPTURE OF RETAINING WALLS DURING EARTHQUAKE

Example 1.-----Retaining walls in Tokyo-----No earthquake resistant design has been applied to low retaining walls in this area. There are relatively high retaining walls resulted from adding extensions on top of the low retaining walls, because this area has severe land subsidence. As a matter of fact, if the Mononobe-Okabe formula had been correct, those retaining walls would have been destroied by earthquakes. But no damages occured yet.

Example 2.-----Concrete block retaining wall in Izu-----Figure 1 shows a broken retaining wall of concrete blocks. A horizontal crack appeared at the middle hight of it, and the upper part inclined toward the backfill, which settled about one meter. If the conventional idea of earthquake earth pressure had been true, this kind of rupture would have never happened. This phenomena was observed with a simple model test in our laboratory.

Example 3-----Retaining wall constructed on liquefiable foundation in Niigata-----A cantilever retaining wall with pile foundations was constructed on liquefiable foundation in Niigata. This retaining wall moved out horizontally during earthquake due to liquefied ground. The backfill settled about one meter.

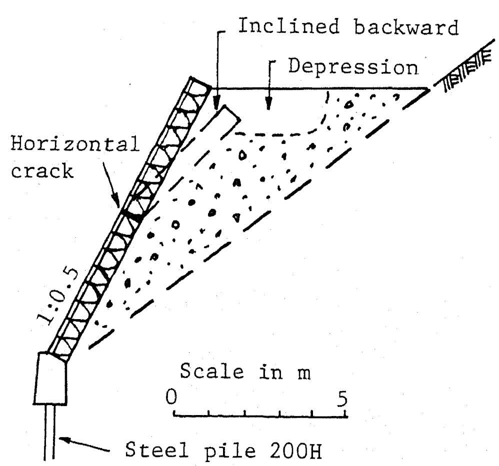
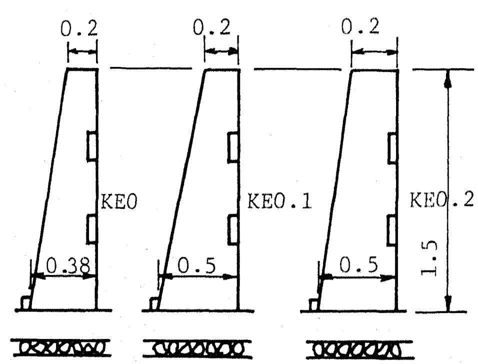


Fig.1 Broken concrete block retaining wall.



(Unit: m)
Fig.2 Gravity walls tested.

EARTH PRESSURE MEASUREMENT WITH GRAVITY RETAINING WALLS

Earth pressure measurement with gravity retaining walls was performed utilizing the earthquake swarm at Matsushiro in 1965 - 6. The design horizontal seismic coefficients KE of the three retaining walls shown in Fig. 2 are 0, 0.1, and 0.2 respectively. The Mononobe-Okabe formula was used for calculation. No retaining walls were overturned by earthquakes of 45, 65, and 73 gals in acceleration. Maximum earthquake earth pressures measured were 2-20 % larger than the ordinary earth pressuree measured. The earthquake earth pressures measured were 9-16 % larger than those obtained with Mononobe-Okabe formula.

EARTH PRESSURE MEASUREMENT WITH CANTILEVER RETAINING WALL (I)

Figure 3 shows a cross section of the prototype model retaining wall with panel type earth pressure gauges and accelograms.

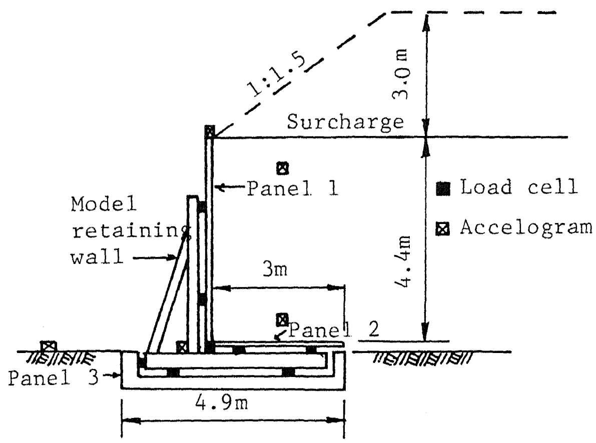


Fig. 3 Model retaining wall with panel earth pressure gauges and accelograms

Soil properties of backfill soil are as follows. Density γ=18.8 kN/m^3, cone resistance q_c=104 kN/m^2, cohesion c=38-90 kN/m^2, angle of internal friction ϕ=3.5 -21.5 degrees, and soil type is cohesive soil (ML). Some of the records obtained were presented to the Case History Volume (Ref. 1). Earth pressures on the retaining wall had been varying with time. Ranges of variation were 213-280 with vertical component, and 90-125 kN/m with horizontal component on the lower face of the base plate. Five earthquakes were recorded during 254 observation days. Maximum acceleration α_m of each earthquake had the following tendency in size.

Ground > higher part of retaining wall > lower part of retaining wall

Figure 4 shows relationship between the maximum acceleration of ground and horizontal component of base resistance,R. Total amplitude is used for both acceleration and earth pressure. Total weight of the backfill, which is shown by the hatched area in Fig. 4, multiplied by the muximum acceleration α_m is less than the horizontal component of base resistance R.

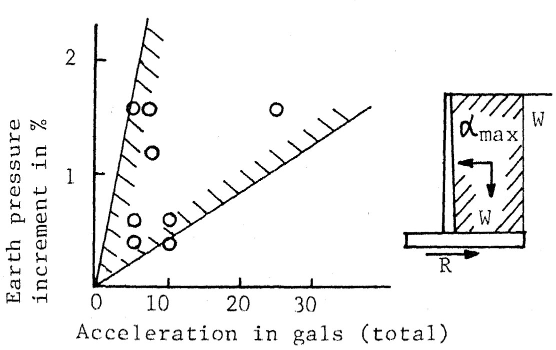


Fig. 4 Acceleration of ground versus earthquake earth pressure increment

Percentage of addition and reduction of normal earth pressure by earthquakes on the vertical wall and that of the friction on the upper face of the base plate were almost equal.

The largest earthquake occurred on July 8, 1974. Table 1 presents comparison of earth pressures between the observed horizontal component of base resistance and the calculated ones. Earth pressure at ordinary time computed by the Coulomb's formula is much smaller than the observed static earth pressure. Therefore, earthquake earth pressure by the Mononobe-Okabe formula with the horizontal seismic coefficient 0.3 is 101 kN/m, which is almost equal to the earth pressure at ordinary time. The time history response analysis method was impossible to apply to the analysis, because retaining wall with backfill was too complicated.

Table 1. Comparison of measured and calculated earth pressures of horizontal component in kN/m

	July 8, 1974		April 8, 1975	
	Calculated	Measured	Calculated	Measured
Ordinary time	60.6	104.0	175.0	140.0
Earthquake time	62.1	104.9	195.0	150.0
Increment	1.5	0.9	20.0	10.0

EARTH PRESSURE MEASUREMENT WITH CANTILEVER RETAINING WALL (II)

The surcharge load was applied upon the backfill of the retaining wall as shown in Fig. 3 on December 10, 1974. Relatively large earthquake took place on April 8, 1975. The curves showing acceleration and earthquake earth pressure were quite complicated, therefore one could not find a simple relationship between acceleration and earth pressure (Ref. 1). Comparison is made between the measured earth pressure and the calculated ones by the Coulomb-Mononobe-Okabe formula (Table 1). Earth pressure at ordinary time with Coulomb's formula increases remarkably when the surcharge is applied, but it does not increase so much from the result of measurement.

EARTH PRESSURE MEASUREMENT WITH LARGE CONCRETE BLOCK RETAINING WALL

Using erathquake swarm at Mt. Usu, active volcano, backfill earth pressure against the backside of the large concrete block retaining wall were measured with 4 panel type earth pressure gauges. Figure 5 shows the cross

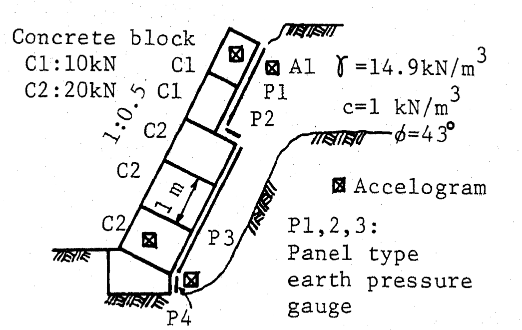


Fig. 5 Large concrete block retaining wall

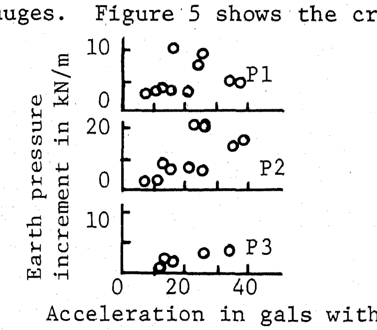


Fig. 6 Acceleration versus earth pressure

section of the large concrete block retaining wall. In order not to be destroied by severe earthquakes, the front face of the retaining wall was given by the inclination of 1:0.5, and the base was placed on concrete piles. Four accelograms were installed. The records were obtained, but the earthquakes were not so large. The accelerations of the upper part were 1.8 times larger than those of the lower ones. Fig. 6 shows relationship between the accelerations at the upper part of the backfill and the vertical components of earth pressure at panels P1, P2, and P3. Fluctuations of earth pressure at the upper part was larger than those at the lower part. The cause of this phenomena may be due to the difference of acceleration between them. If the acceleration had become very large, the uppermost block would have tilted backward as the result of reduction of earth pressure at the back side of the block. Earth pressures on the back sides of the retaining wall cannot be calculated by the Coulomb's formula. One example of the measurement is reported elsewhere (Ref. 2).

EARTH PRESSURE MEASUREMENT WITH MULTIPLE ANCHORED RETAINING WALL

The multiple anchored retaining wall used for measuring earth pressure is composed of the front wall with columns and concrete plates, and anchors with steel bars and concrete plates. The sketch of the retaining wall is shown in Fig. 7. Soil properties of the backfill are given in Table 2. Four reinforcement gauges, 13 earth pressure gauges, and 9 sets of wire strain gauges were installed for measuring earth pressures at ordinary time. Four reinforcement gauges and 2 accelograms were used at earthquake time. Readings of reinforcement gauges have been changing with time and temperature. Fairly large earthquake took place in Tokyo area, where the test retaining wall was located, on February 27, 1983. The epicenter of this earthquake was situated about 17 km from the retaining wall and about 70 km from the ground surface. The total period of duration was about 60 seconds. The period of the severest vibration lasted about 5 minutes. The records of these seconds were described in Fig. 8. Actually, the earth pressure at ordinary time did not change. The tensile forces measured are shown in Fig. 7.

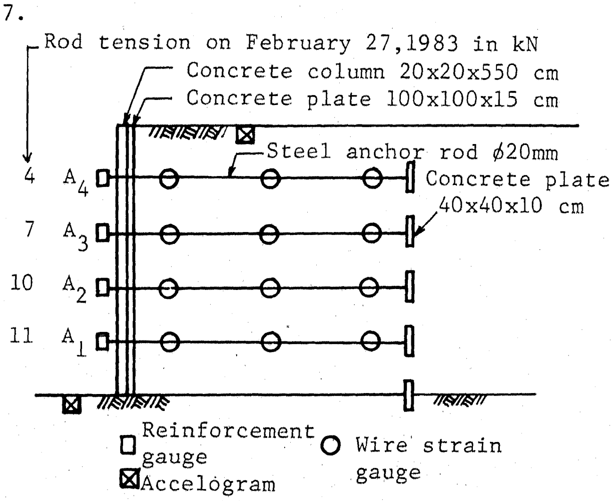


Fig. 7 Cross section of multiple anchored retaining wall

Table 2. Soil properties of backfill

- Unit weight γ=14.6 kN/m^3
- Cohesion c_u=14.6 kN/m^2
- Angle of internal friction ϕ=15 degrees
- Young's modulus E=200-500 kN/m^2
- Poisson's ratio =0.3

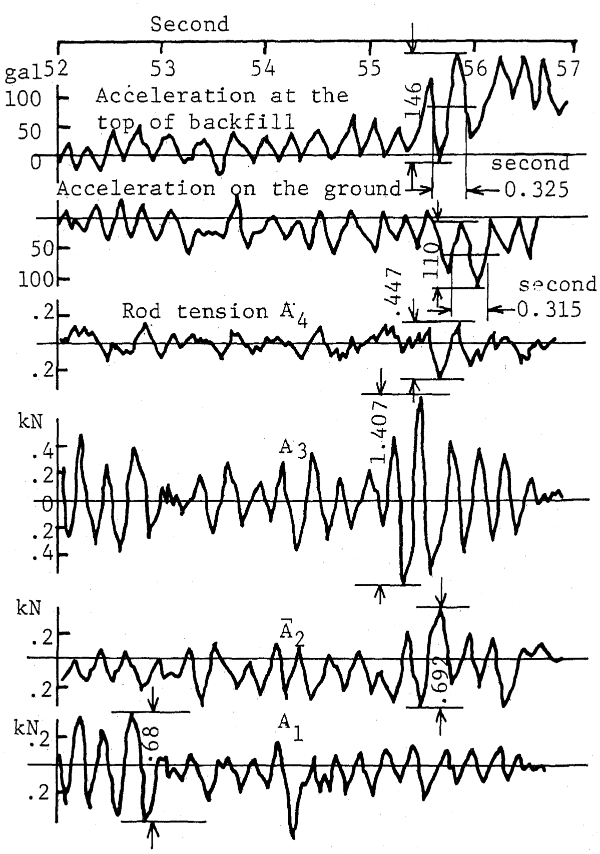


Fig. 8 Accelerations and tensions of rods

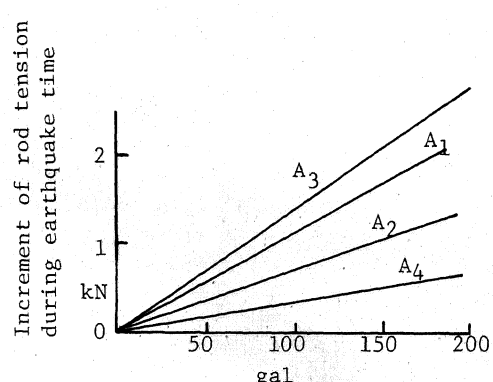


Fig. 9 Acceleration versus increment of rod tension during earthquake time

Horizontal component of earth pressure on the vertical wall was 34.8 kN/m, which is much smaller than that was calculated by Coulomb's formula as 60.8 kN/m. The coefficient of earth pressure at rest is only 0.19, which is much smaller than that of Coulomb's 0.33 and that of the cantilever retaining wall reported in this paper 0.5. The reason why the coefficient of earth pressure was so small is due to the method of construction and that the anchors could easy be pulled out with weak pulling forces.

The recorded curves of acceleration and rod tension are divided at intervals of one minutes through the period of earthquake. Maximum or minimum amplitudes of the rod tension in each interval are compared by using a graph, as shown in Fig. 9. The increase of rod tension becomes larger in proportion to acceleration. The increase and decrease of earth pressure on the retaining wall are not necessary equal to those of rod tensions. Because, effect of inertia force on the wall should be taken into account. Measurement of earth pressure with earth pressure gauges during earthquake were not performed. Therefore, estimating earthquake earth pressure should be done indirectly. Figure 10 is a sketch of forces acting on the retaining wall. The following equation may hold between the inertia force I_f, tension of rods T, and total earth pressure P.

$$P = T - I_f \quad ----- \quad (1)$$

Total weight of the retaining wall is 22.31 MN/m. Inertia force is obtained by multiplying the total weight of the retaining wall by acceleration. Assuming the acceleration of the wall body is equal to that of the surface of the backfill, curves shown in Fig. 11 (a) is obtained. Using the curves in Fig. 8, the total force of the anchor rods is also obtained as indicated in Fig. 11 (a). From these two curves the curve showing earth pressure is drawn as in Fig.11 (b). Both the inertia force and rod tension contain errors, because they are calculated on a bold assumption. But a general idea may be understood by this figure. The earth pressure does not simply increase by earthquake. If the inertia force acts to the forward direction, earth pressure may decrease. On the contrary, if the inertia force acts to the backward direction, the earth pressure may increase. Maximum or minimum earth pressure due to earthquake is +1.25 or -1.50 kN/m respectively, and these are +3.4 or -4.3 % to the total earth pressure at ordinary time. Assuming the earth pressure increases in proportion to the acceleration, the increase in earth pressure for the acceleration of 300 gals will be only 20 % of the earth pressure at ordinary time. Figure 12 shows earth pressures calculated with Coulomb-Mononobe-Okabe's formula and measured by the authors. Difference between them is obvious.

For the purpose of designing wall body of the retaining wall, the earth pressure on the back of the retaining wall may be used. For the purpose of designing anchor rods, Table 3 may be utilized as a reference. In this way designing earth pressure should be changed in response to the parts of structures. As the results of laboratory model tests, the following facts were found. As the acceleration increases, the the wall body begins to separate from the backfill. The earth pressure becomes zero accordingly.

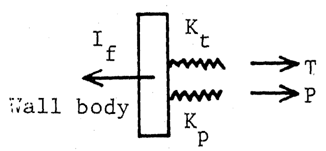
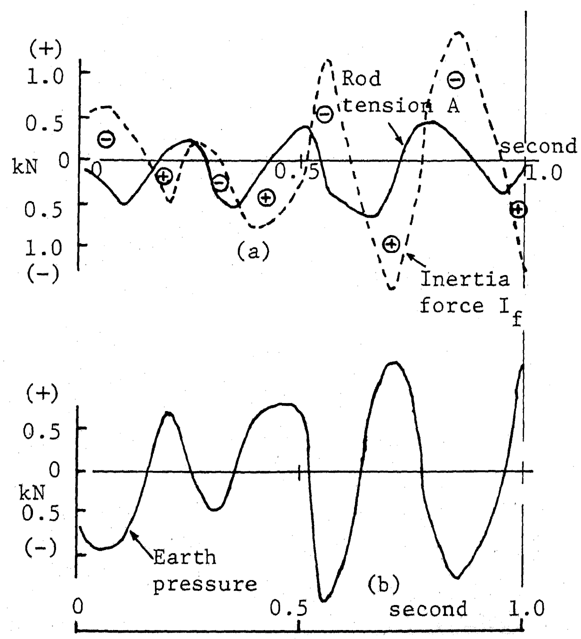


Fig. 10 Sketch of forces acting on retaining wall



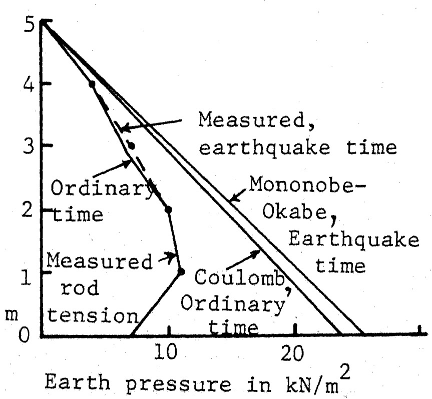


Fig. 12 Earth pressure calculated and measured

Fig. 11 Inertia force on retaining wall body, rod tension, and earth pressure

Table 3. Ratio of rod tension increment in earthquake time with rod tension at ordinary time on Feb. 27, 1983

	Ordinary kN	Increment kN	Ratio %
A1	4	0.23	5.75
A2	7	0.70	10.00
A3	10	0.35	3.50
A4	11	0.38	3.45

The retaining wall does not collapse completely, because anchors are alive. If much higher accellation is given, plastic failure takes place in the backfill, and the wall moves forward in a large scale. Generally, it is believed that high pressure appears at the back face of the retaining wall, and pushes out or overturn the retaining wall. But this is not the only way of rupture. Retaining walls with cohesive soils as backfill can stand without having retaining walls at their front. In this case earth pressure on the wall would be zero, when the retaining wall collapses.

CONCLUSIONS

1. Magnitude of earthquake earth pressure is not determined by acceleration acting at that moment, but determined by the total energy put into the retaining wall system (wall body and backfill near to it) in one or two seconds.
2. Distribution of changing in earth pressure on the back of the retaining wall is not a triangular shape, the base of which is at the wall bottom. Pressure fluctuation at the top is larger than that of the bottom with a certain condition. When the earth pressure at the top decreases to zreo and the inertia force of the wall body acts backward, the upper part of the wall is broken and bent backward.
3. During earthquake time, temporary fluctuation of earth pressure appears starting from the earth pressure at ordinary time. Therefore, earth pressure at ordinary time is very important. The earth pressure at ordinary time varies with many factors. Coulomb's formula is only a rough estimation. Mononobe-Okabe formula is based on Coulomb's formula. Therefore, it has the same defect as the Coulomb's one.
4. Rupture of retaining walls begins with wall body or backfill. Cause of wall body failure is combination of inertia force acting on the wall body and earth pressure. Rupture of backfill occurs when the earth pressure on the wall decreases, due to the outward displacement of the wall body. High strength of the backfill is needed to prevent this type of failure.

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