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Static and Dynamic Behaviour of Cohesionless Backfill behind a Rigid Unyielding Wall

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ABSTRACT

In this research the lateral earth pressure distribution, ground settlement and soil densification behind model rigid unyielding walls fixed at the top and the bottom under dynamic conditions was investigated using a shake table. Several parameters such as: lateral extent of the backfill, the relative density of the backfill material and the frequency of the base motion were varied in the experimental programme.

INTRODUCTION

The determination of static and dynamic lateral earth pressures on retaining structures is required for safe and economical design of such structures. The lateral pressure depends on the type of soil and the flexibility of the structure. Extensive analytical and experimental research has been conducted to investigate the mobilized earth pressure distribution behind retaining structures.

One of the most common examples of earth retaining structures is a basement wall. These walls are normally built of reinforced concrete and can be considered as rigid. These walls are typically restrained from translation and rotation because of the supports at the top and the base and do not produce a state of plastic equilibrium behind the wall. Consequently, only at-rest conditions of earth pressures apply for such walls under static conditions.

The earliest method for determining the dynamic lateral earth pressures against retaining structures using the limit equilibrium approach was developed by Mononobe (1924) and Okabe (1924) in the 1920's. The Mononobe-Okabe method was later extended by Prakash and Basavanna (1969) to give a more realistic distribution of earth lateral earth pressures, and Seed and Whitman (1970) proposed a simple dynamic design criteria for retaining structures based on the Mononobe-Okabe method.

Matsuo and Ohara (1960) proposed an elastic solution to determine the dynamic earth pressure behind rigid quay walls by using a two-dimensional analytical model. The backfill soil was assumed as a homogeneous elastic layer with no vertical displacements. The wall was assumed to be stationary and the basic equations were derived according to wave theory. Shake table experiments by Matsuo and Ohara were in good agreement with their theoretical predictions for rigid walls.

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Wood (1975) studied the behaviour of rigid unyielding retaining walls subjected to earthquake motions and proposed static and dynamic solutions based on linear elastic theory. Wood's analysis is based on the response of a stratum of finite length excited uniformly along its base and two vertical end boundaries. Wood applied this theory to a wall of a power station founded on rock and showed that the Mononobe-Okabe method may not be suitable for the rigid walls founded on rock or pile foundations.

Scott (1973) presented a simple model to study the dynamic response of a semi-infinite and bounded elastic stratum. Recently, Velestos and Younan (1994) have presented solutions for a semi-infinite, uniform, viscoelastic stratum of constant thickness which is excited by a space-invariant motion along its base and its vertical boundary. The method of analysis used by Velestos and Younan is similar to Matsuo and Ohara (1960).

Siller, etal (1991) have presented solutions for dynamic earth pressures on gravity and anchored walls considering non-linear and hysteresis properties of the backfill.

Each of the analytical approaches discussed above have some limitations regarding the validity of assumptions involved and, therefore, many researchers have conducted experiments to verify the earth pressures estimated from analytical studies. A significant number of experimental studies deal with retaining walls which were allowed to rotate either about their base or their top. These types of motions are not consistent with a bridge abutment or a basement wall type structure.

More recently, Yong (1985) showed experimentally that the Mononobe-Okabe method is not suitable for computing the dynamic incremental force for rigid unyielding retaining walls. The author concluded that the elastic theory by Wood (1975) and the New Zealand National Society of Earthquake Engineering study group's recommendation (Yong, 1985) both provide a reasonable prediction for the dynamic incremental force for the loose backfill and a good estimation for the dense backfill. Yong also observed the settlement which occurred in the backfill as the result of earthquake vibrations. It was observed that substantial settlements occurred for loose backfill materials while insignificant settlements were observed for dense backfills. However, Yong does not present any quantitative data on settlements.

Despite the extensive experimental studies on model walls, conflicting opinions exist on the nature and magnitude of dynamic earth pressures. The effect of varying the lateral extent of the backfill has not been studied and no quantitative information has been reported regarding the settlement and changes in physical properties of the backfill due to dynamic excitation. Hence, the research presented in the rest of this paper attempts to address some of these issues.

TEST SETUP

Many previous researchers have recommended that the estimation of dynamic earth pressure should be supported by information obtained from tests conducted on properly designed model wall structures as testing of a prototype structures is expensive and time consuming. Since the exact modelling of the structure is difficult because of the complex scaling laws, the model testing described in this paper is considered to be similar to a small prototype structure. In addition, the behaviour of the model is compared with the results predicted by available methods of analysis without any attempt to extrapolate the experimental data to prototype structures.

The test system was mounted inside a rectangular test box 1670 mm long, 315 mm wide and 1023 mm high and was used to simulate a strip of a retaining wall and its backfill under plane-strain conditions (Fig. 1). The model retaining wall, 12.7 mm thick steel plate, was placed in the box and secured to the end plate of the box by two channels, one at the top and the other at the bottom of the wall. A 12.7 mm thick steel plate secured to the box frame at the top and the bottom formed the other end of the model. This steel plate could be moved within the box and thus the lateral extent of the backfill could be varied in the experiments.

A total of 8 measurements were taken in this research using various instruments as shown in Figure 2. Four diaphragm type pressure transducers were mounted on the centre line of the wall surface and two universal flat load cells were fixed at the top and the bottom on the centre line of the wall to measure the reactions generated by the soil pressure. In addition an accelerometer was mounted 40 mm from the top of the wall and was used to measure the wall and, consequently, the base acceleration. The shake table displacement was measured using a displacement transducer.

A uniform dry silica sand was used in all the experiments. The uniformity coefficient of the sand was 2.1 and all the particles were smaller than 2.5 mm. The relative density of the silica sand was varied in the experimental programme. The relative density of the loose silica sand was 20% and the angle of shearing resistance was determined to be 37.5° from direct shear tests. The relative density of the dense silica sand was 80% and the angle of shearing resistance was determined to be 48.5°. The unit weight of the loose silica sand bed on average was 14 kN/m^3 and that of the dense bed was 15.5 kN/m^3.

The sand was placed behind the model retaining walls by an air pluviation technique to achieve either loose or dense relative densities. This technique has been used by many researchers to form consistent sand beds in the laboratory.

TEST PROCEDURES

Two series of tests were conducted, one with a loose backfill and the other with a dense backfill. In each series the lateral extent of the sand backfill was varied in order to study the effect of different length/height (L/H) ratios of the backfill on the lateral earth pressure distribution. Tests were carried out for L/H's of 1.37, 1.17 and 0.97.

Initial readings were taken immediately after the test box was filled with sand in order to establish the static earth pressures. Following the measurement of the static soil pressures, a series of dynamic tests were carried out. These tests involved the application of a sinusoidal base acceleration to the test box and monitoring the resulting soil pressures and wall reactions. The peak table acceleration was kept in the range of 0.4g to 0.6g, the frequency of the motion was set at 7, 8, 9 or 10 cps and the duration of the excitation at each frequency was 13.7 seconds. Each test setup was in fact tested four times. First, at the 7 cps, then at 8 cps, then at 9 cps and finally at 10 cps. After each excitation the shake table was stopped and the profile of the soil behind the wall was measured by recording the soil height at 50 mm increments from the wall face.

In order to study the densification behaviour of the backfill, cone penetration tests were carried out at three different locations behind the wall both before and after the 10 cps dynamic tests. The miniature cone was 12.7 mm in diameter with a 60° apex angle. The cone was pushed into the sand at a constant rate of 8 mm/min and the resistance was measured after every 50 mm of penetration.

RESULTS AND DISCUSSION

The data from the pressure transducers and load cells are presented in Figures 3 and 4 for loose and dense backfills, respectively. The data show that the static earth pressure distribution behind an unyielding retaining wall can be approximated by a straight line. These results also indicate that Jaky's equation [$K_0 = 1 - \sin \varphi'$, where φ' is the effective angle of friction] overestimates the static at-rest earth pressure for the loose backfill but gives a close estimate for the dense backfill, if the data from the load cells is used. It was also evident that the effect of varying the L/H ratio of the backfill on the static at-rest earth pressures was insignificant.

It is interesting to note that the diaphragm type pressure transducers used in the study showed lower earth pressures than the estimated earth pressures from the load cell data. Similar observations have been made by Yong (1985) in his experimental studies also. As many of the previous researchers have only used pressure transducers, the accuracy of static as well as dynamic earth pressures is thus questionable.

The dynamic lateral pressure distributions are presented in Figures 5 and 6 for loose and dense backfills, respectively. It was found that the pressure distribution was nonlinear with depth and maximum pressure always occurred at the base of the wall. In addition, extrapolation of the data showed that the pressure decreased in a nonlinear manner towards the top of the wall and a non-zero pressure exists at the top of the wall. In all cases, the point of application of the total dynamic pressure thrust was calculated to be between 0.39H and 0.41H from the base of the wall. Figures 5 and 6 are for L/H ratio of 1.37. Similar trends were observed for L/H ratios of 1.17 and 0.97. The data presented in Figures 5 and 6 are from pressure transducers only and the actual pressures may be somewhat higher assuming that the trend discussed above for static conditions also applies for dynamic tests.

Settlement of the backfill soil was recorded after the dynamic excitation of the model wall at each testing frequency. Figures 7 and 8 show typical soil profiles after settlement had occurred. In all cases the maximum settlements occurred at the soil-wall interface and decreased away from the wall to a constant value. Figures 7 and 8 are for L/H ratio of 1.37. Similar trends were observed for L/H ratios of 1.17 and 0.97. The settlement data for the loose backfill show that the maximum settlement at the soil-wall interface varied between 7.3% and 9.2% of the height of the backfill for different L/H ratios. It decreased further away from the wall and became constant at about 0.28H from the model retaining wall. The maximum settlement for the dense backfill varied from 3.1% to 3.7% of the height of the backfill for different L/H ratios. The settlement in this case levelled off at about 0.33H from the back of the wall.

Figure 9 shows that data from the miniature cone penetration test for L/H = 1.37, and loose relative density of backfill. The cone penetration tests were performed at distances of 0.16L, 0.32L and 0.48L behind the back of the wall before and after dynamic excitation. The data before dynamic excitation shows that the soil bed prepared using the air pluviation technique resulted in a uniform sand bed. Following the dynamic excitation, the cone data indicated that the relative density of the sand bed was increased but was independent of the distance from the back of the wall. The sudden increase below a depth of 800 mm after densification was due to the presence of the rigid bottom boundary.

Figure 10 shows the comparison between the experimentally measured dynamic earth pressures, the Matsuo-Ohara solution, and the New Zealand National Society of Earthquake Engineering (NZNSEE) Group's recommendation for dense backfill for L/H = 1.37. The following properties were used for the Matsuo-Ohara solution: E_s = 45,000 kPa and Poisson's ratio = 0.3. Similar observations were also made by Yong (1985) who compared his experimental data with Wood's (1975) solution and the NZNSEE's recommendation.

CONCLUSIONS

The following conclusions can be drawn from the experimental study reported in this paper.

1. The New Zealand National Society of Earthquake Engineering recommendation for dynamic earth pressure is conservative but can be used as an upper bound in the design.
2. The settlement of the backfill is non-uniform behind the rigid retaining wall and depends significantly on the initial relative density of the backfill. The settlements were uniform beyond a distance of 0.3H behind the wall irrespective of the initial relative density.
3. The soil densification after dynamic excitation was uniform behind the rigid unyielding wall.

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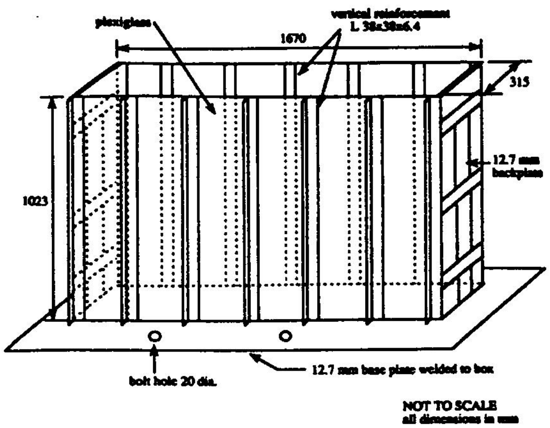

Fig. 1. Test Box

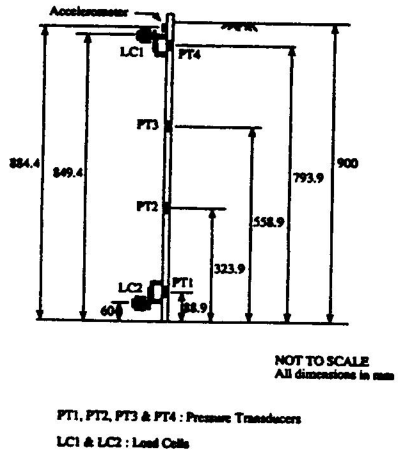

Fig. 2. Instrumentation of model wall

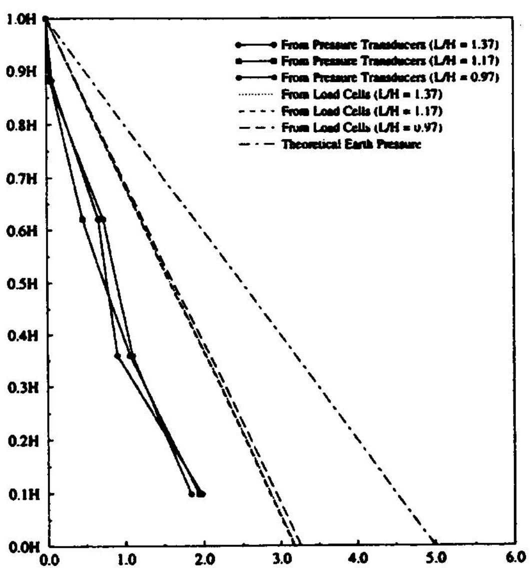

Fig. 3. Static earth pressure distribution
- loose backfill

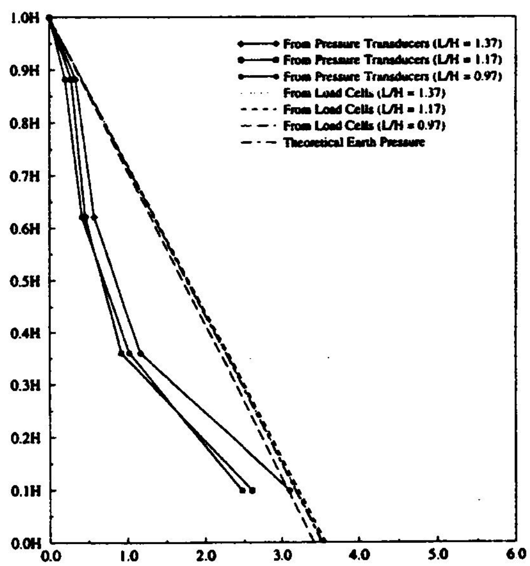

Fig. 4. Static earth pressure distribution
- dense backfill

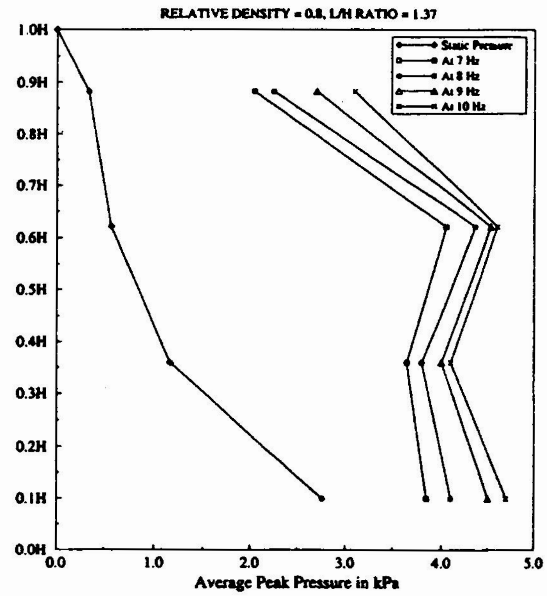

Fig. 5. Dynamic earth pressure distribution - dense backfill

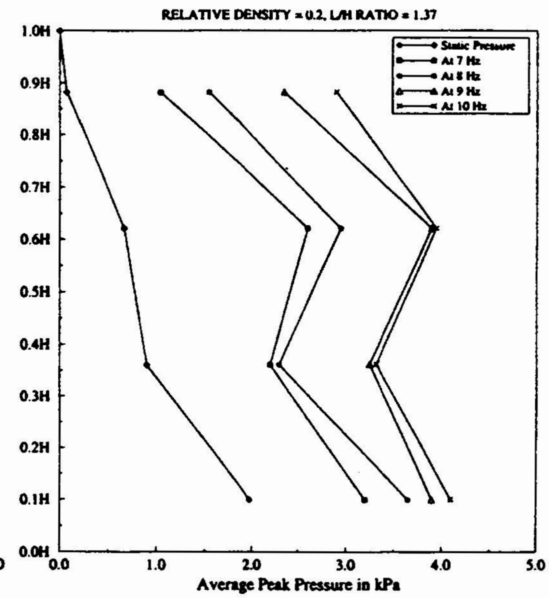

Fig. 6. Dynamic earth pressure distribution - loose backfill

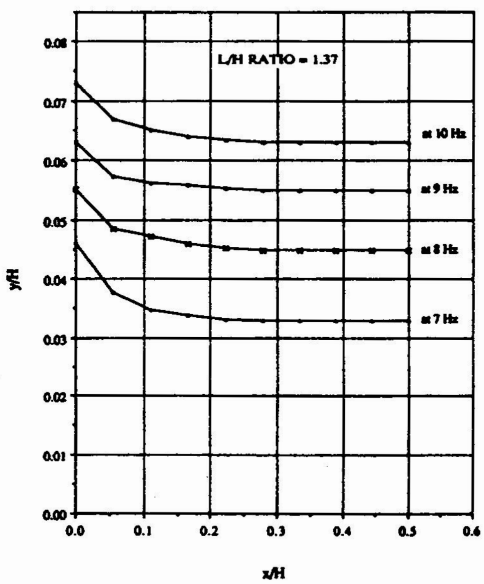

Fig. 7. Cumulative settlement - loose backfill

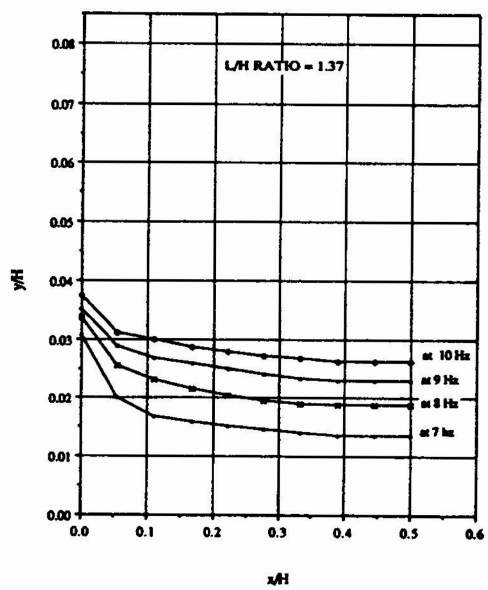

Fig. 8. Cumulative settlement - dense backfill

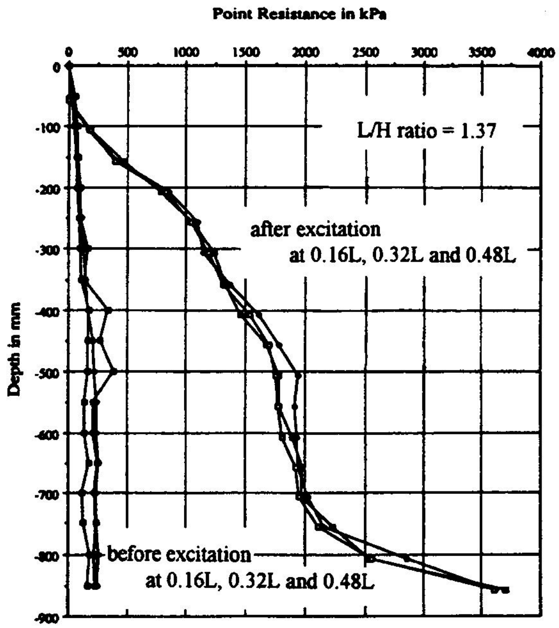

Fig. 9. Cone penetration test data - loose backfill

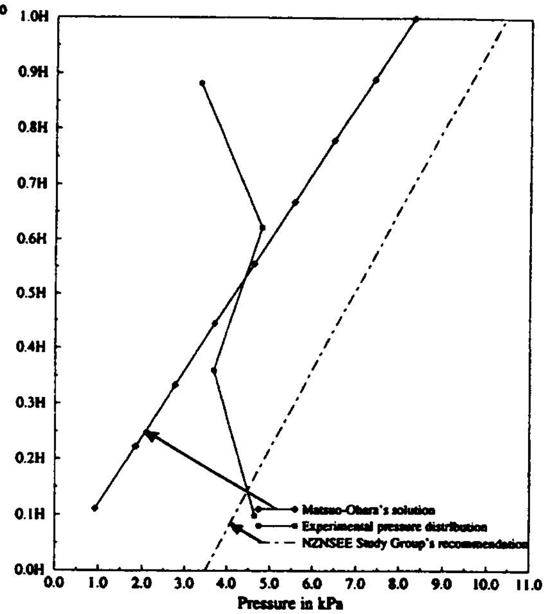

Fig. 10. Comparison of experimental and theoretical earth pressure distribution for dense backfill