EARTHQUAKE RESPONSE OF GRANULATED COAL ASH BY ONLINE TESTING

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ABSTRACT :

Coal ashes discharged from coal-fired power plants have recently been gaining attention as a new form of geomaterials. They have been popularly used as ground materials for the improvement of unsuitable soil and for foam-mixed solidified soil. However, development of more applications is needed in the light of the enormous amount of coal ash generated. The present study was performed to confirm the applicability of granulated coal ash as reclamation material with adequate resistance against liquefaction during an earthquake. For this purpose, online pseudo-dynamic response tests were performed using a hollow torsional shear test apparatus. For comparison purposes, similar tests were performed using Toyoura sand, and the difference in the seismic response of the two materials is discussed. The results obtained clarified the behavior of granulated coal ash when subjected to cyclic loading due to earthquakes.

KEYWORDS: earthquake response, granulated coal ash, online testing, hollow torsional shear test

1. INTRODUCTION

Coal makes up about 20% of the primary energy source in Japan and it has not changed since the 1970s. However, it is inevitable for coal consumption to keep on increasing every year because of the increase in the amount of energy demand. As a result, the amount of coal ash generated every year increases. Therefore, it is necessary to look for options whereby coal ash can be utilized effectively.

Currently, 80% of the total amount of coal ash produced is being recycled, with the majority being used in cement and in civil engineering works. Considering the latter, the utilization of coal ash is expected to increase from now on since large volume of ash could be used at any given time. The utilization of coal ash in civil engineering works, such as in reclamation or as backfill material, subgrade material and soil improvement material, has already been reported. For example, the applications of coal ash to geotechnical engineering have been investigated by many researchers, such as Horiuchi et al. (1995) and Sawa et al. (2002).

The authors have been studying the mechanical properties of granulated coal ash formed by milling process, with small amount of cement added and whose particle size is almost equivalent to that of sand or fine gravel (e.g., Yoshimoto et al., 2005; Yoshimoto et al., 2006a, b; Yoshimoto, 2007). Granulation affords improved work efficiency, and because dispersion is prevented, the material is convenient to store. The material can be handled in the same manner as ordinary soil. The use of granulated coal ash has many advantages, such as the suppression of leaching of heavy metals and the possibility of outdoor curing.

This research was performed to confirm the applicability of granular coal ash as reclamation material with adequate resistance against liquefaction during earthquake. Because of its different index properties, it is believed that the seismic response characteristics of granulated coal ash during earthquakes are different from those of natural sand. Therefore, online pseudo-dynamic response tests were performed to understand such difference by comparing the response characteristics of granulated coal ash with those of natural sand.

2. MATERIALS USED

Granulated coal ash is a material that is modified by adding cement, water and additives to the coal ash, and the mixture is granulated by mixing and rotating. The granulated coal ash used in the test, consisting of 85% coal ash, 5% cement and 10% additives by weight, was manufactured using a motor mixer with 10m^3 capacity. The material was cured under water content of w=40%. Because of the limitation of the testing equipment, the particle size used was less than 2.0 mm. The appearance of granulated coal ash is shown in Figure 1. It can be observed that granulated coal ash looks similar to ordinary sand or fine gravel, with round-shaped particles.

(a) (b)

Figure 1: (a) Granulated coal ash: (b) enlarged view of a particle

In the examination of the behavior of granulated coal ash, Toyoura sand was also employed for comparison purposes. Table 1 shows the physical properties of the samples used while Figure 2 illustrates the grain size distribution curves. Note that the specific gravity of the particles of granulated coal ash is very low compared to natural sand because of the presence of air vesicles in individual grains. In particular, the maximum and minimum void ratios of granulated coal ash, which were determined using the methods specified in the Japanese Geotechnical Society (JGS) standards, were found to be very large as compared to those of Toyoura sand.

Table 1: Properties of materials used

Sample	G_s	e_{max}	e_{min}	U_c
Toyoura sand	2.643	0.973	0.635	1.200
Granulated coal ash	2.285	2.280	0.966	4.957

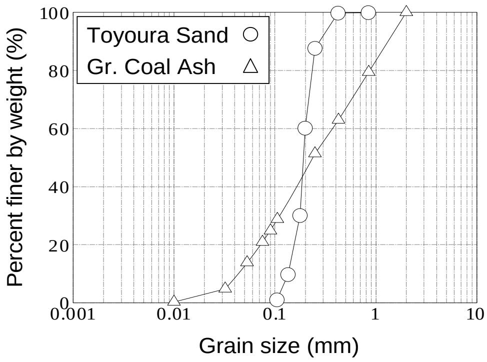
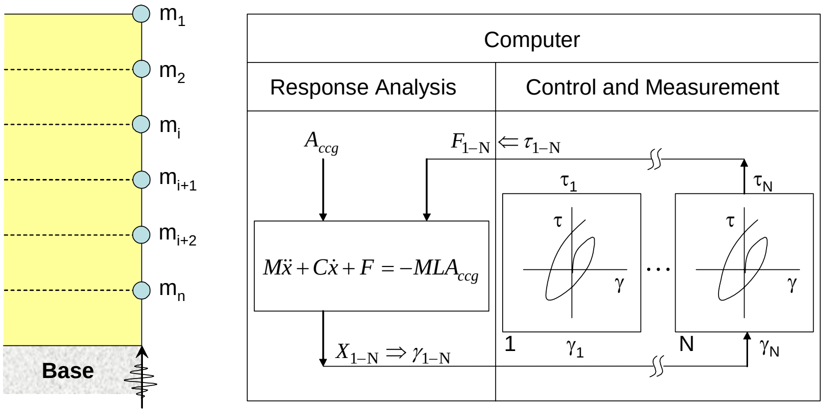


Figure 2: Grain size distribution curves of the materials used

3. ONLINE PSEUDO-DYNAMIC RESPONSE TEST

3.1 Basic Concept

Online testing is a method of modeling earthquake effects by obtaining soil response characteristics directly from soil samples rather than by multi-parameter constitutive models. The principle of the online pseudo-dynamic response test for the analysis of level ground is shown in Figure 3.



(a) lumped mass model (b) algorithm used

Figure 3: Conceptual diagram of online pseudo-dynamic response test

The system, which was initially developed by Kusakabe et al. (1990), involves the following algorithm. First, the ground to be analyzed is converted into a series of lumped mass models subjected to an earthquake excitation at the base (Figure 3a). Next, the dynamic excitation of the mass system is solved using a computer to determine the displacement response of each mass. The shear strain that is equivalent to the resultant displacement is applied to the corresponding specimen under computer control. The restoring forces that are monitored for each soil specimen are then used to calculate the displacement response for the next step (Figure 3b). This process is then repeated for as long as the earthquake motion continues in order to directly determine the constantly changing non-linear restoring force of the ground from the element tests.

Online testing as a one-dimensional method has limitations in its application to practical problems. However, the accuracy of the analysis is not problematic compared with conventional numerical procedures (Takahashi et al., 2006). In the tests presented herein, the element experiment was conducted using a hollow torsional shear test apparatus. In performing the dynamic analysis, the following equations were solved:

$$M\ddot{x} + C\dot{x} + F = -MLA_{ccg} \tag{3.1}$$

where M is the mass matrix; C is the damping matrix, F is the restoring force vector; L is a unit vector; A_{ccg} is the input acceleration vector and x is the displacement vector. The damping is modeled using Rayleigh damping parameters with damping coefficients proportional to the mass and stiffness. The linear acceleration method was used for the initial numerical integration and the central difference method was then used in subsequent steps (Shibata, 1981).

3.2 Model Ground

For the online pseudo-dynamic response tests, the soil profile at the location of the seismometer array in Port Island, which liquefied extensively during the 1995 Hyogoken Nanbu Earthquake, was employed (Kobe City Development Authority, 1995). Instead of the original decomposed granite soil (Masado), the 16 m-thick liquefiable layer was replaced by either granulated coal ash layer or by Toyoura sand layer, as shown in Figure 4. The horizontally layered ground, with total depth of 33 m, was divided into 4 layers, each of which was replaced by a one-dimensional mass model (m_1 to m_4). Due to the limitation of the number of testing equipment, only one layer (S_2) was considered as online layer (where restoring forces are determined), while the rest of the layers are treated as analytical layer (using modified R-O model).

The analytical parameters chosen for the modified Ramberg-Osgood models are also shown in Figure 4. These values were taken as similar to those of the original ground, as reported in the literature. Since the S_2 layer was replaced by either Toyoura sand or granulated coal ash, the parameters of the underlying layers (S_3 and S_4) have to be modified to account for the changes in confining pressure due to the different unit weights of granulated coal ash and Toyoura sand. For example, the initial shear moduli were assumed to be proportional to $(\sigma_c)^{0.5}$, where σ_c is the effective confining pressure (Iai et al., 1990).

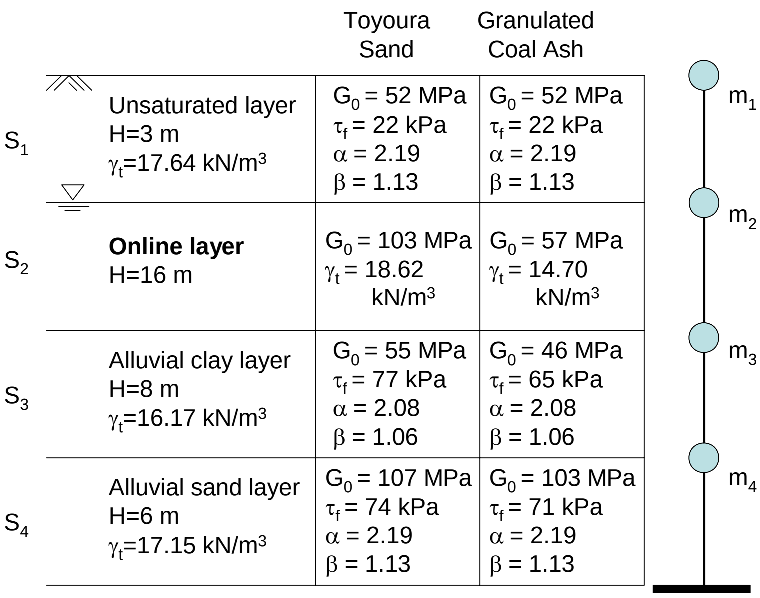


Figure 4: Experimental model used in the online test

3.3 Element Experiments

The element test was carried out using a hollow torsional shear apparatus. Shearing was carried out under undrained conditions assuming zero vertical and volumetric strains. The load was applied using mega-torque motor with maximum capacity of 260 N-m and maximum rotating speed of 28 rpm. For the tests presented herein, the shear strain rate was set at 0.1%/min. Although this is quite less than real time rates, it is commonly accepted that liquefaction and cyclic mobility of sands are dependent on the number of cycles and level of normalized shear stress and independent of frequency (Ishihara, 1993).

The granulated coal ash specimens in the element tests were prepared using water pluviation technique, while the Toyoura sand specimens were formed using air pluviation method, followed by saturation with appropriate back pressure. For both specimens, full saturation was confirmed by checking the B-value. The model specimens, measuring 70 mm high with 35 mm and 70 mm inner and outer diameters, respectively, have initial relative

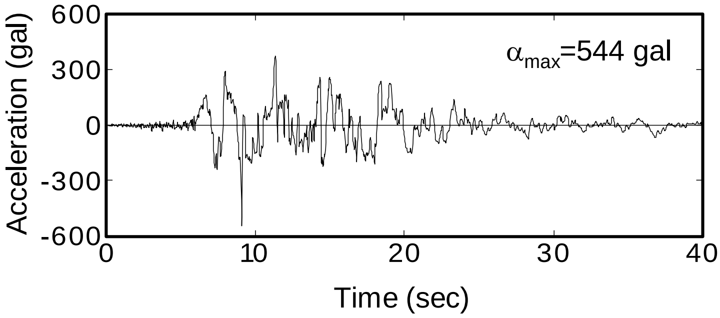


Figure 5: Reference earthquake motion used

densities of D_r=60%. They were consolidated isotropically to an effective confining pressure equal to the overburden stress at the midpoint of S_2 layer (see Figure 4).

3.4 Input motion

For the reference earthquake input motion, the acceleration record observed at location PI-33m NS (maximum acceleration of α_{max}=544 gal) at a depth of 33 m of the seismic array in Kobe Port Island during the 1995 Hyogoken Nambu Earthquake was used (see Figure 5). In the online tests, four (4) levels of input motions were considered, i.e., with maximum amplitudes of 30%, 50%, 70% and 100% of the reference earthquake motion, in order to investigate the seismic response of the model grounds to various degrees of excitations.

4. TEST RESULTS AND DISCUSSION

Typical results of the online pseudo-dynamic response tests are shown in Figure 6, where the acceleration time histories at the surface of each layer (S_1-S_4) for model grounds containing granulated coal ash and Toyoura sand are illustrated corresponding to an input acceleration equal to 100% of the reference input motion. It can be observed that the acceleration response for S_3 and S_4 layers are almost similar, and characterized by high frequency components. However, as the earthquake wave propagated through S_2 layer, the acceleration underwent different degrees of de-amplification accompanied by filtering of the high frequency components. These phenomena are associated with the liquefaction of S_2 layer. The accelerations on the ground surface were almost similar for both model grounds.

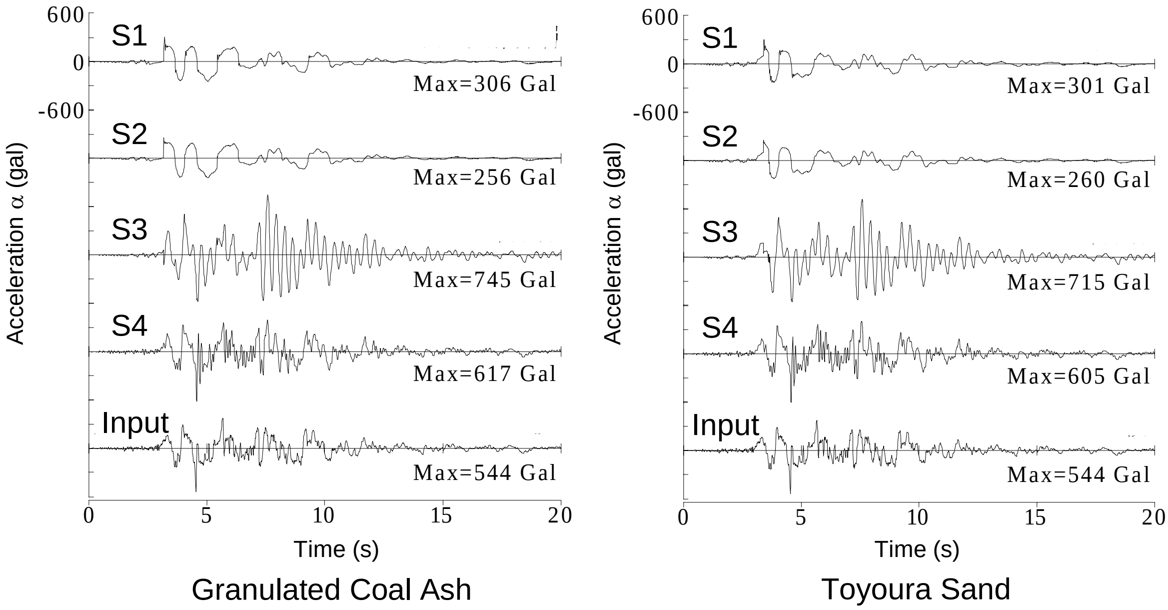
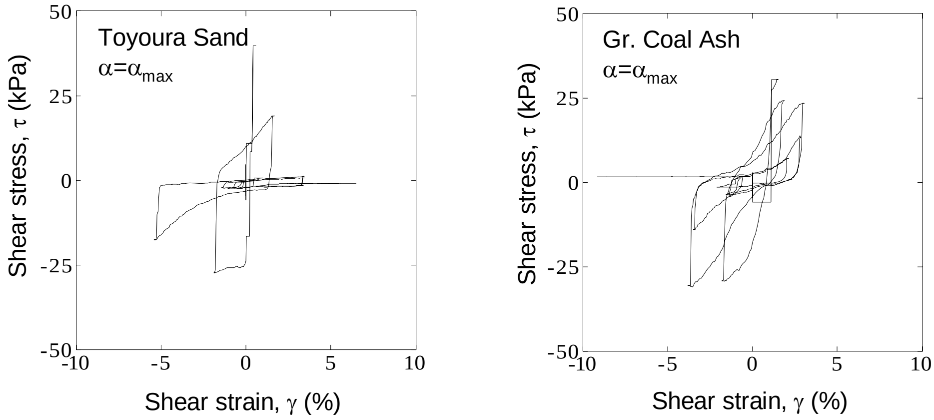


Figure 6: Acceleration time histories for granulated coal ash and Toyoura sand for input acceleration equal to 100% of reference motion.

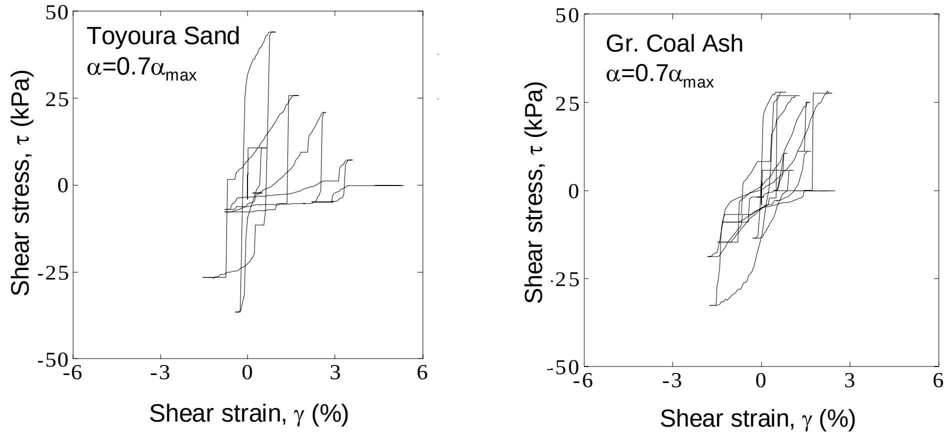
To verify that indeed S_2 layer had liquefied, the shear stress-shear strain relations are plotted for both granulated coal ash and Toyoura sand layers, and these are shown in Figure 7. It can be seen that Toyoura sand underwent stiffness degradation followed by the development of large deformation after only a few number of cyclic load application. Similar pattern was observed for granulated coal ash, although large deformation occurred after a greater number of cycles. These large deformations and reduction in stiffness of the grounds are indications of the occurrence of soil liquefaction.



(a) (b)

Figure 7: Stress-strain relation for (a) Toyoura sand; and (b) granulated coal ash for input acceleration equal to 100% of reference motion.

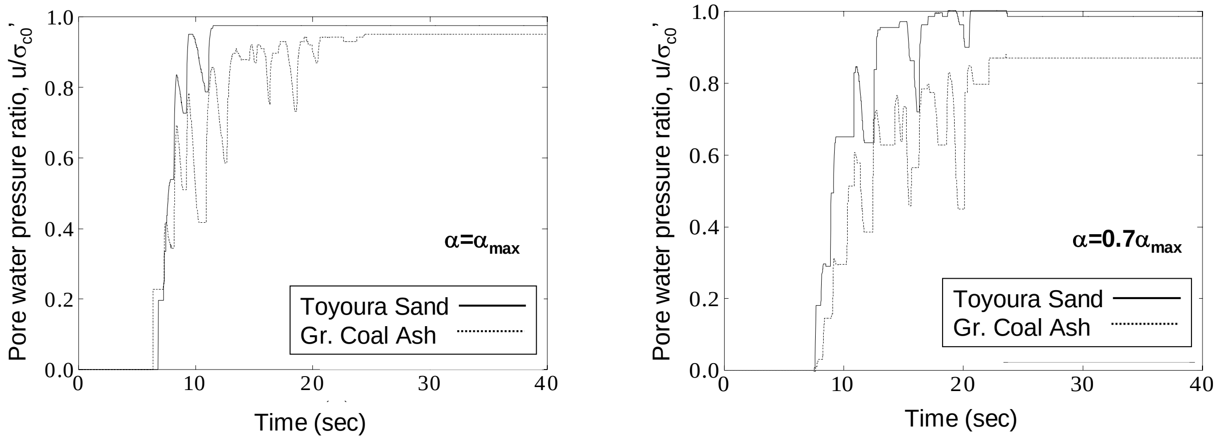
Succeeding online test results for other amplitudes of input acceleration showed that Toyoura sand layer would liquefy if the acceleration amplitude exceeds 50% of the reference earthquake motion. On the other hand, test results for granulated coal ash indicated that it will liquefy only if the amplitude is equal to 100% of the reference earthquake motion. For comparison purposes, Figure 8 shows the shear stress-shear strain relations for both materials at an input acceleration equal to 70% of reference motion. It can be observed that while Toyoura sand showed stiffness degradation after a few cycles followed by development of large strain, the stress-strain relation for granulated coal ash showed otherwise, with much stiffer response as the cyclic loading progressed, and therefore, smaller deformation.



(a) (b)

Figure 8: Stress-strain relation for (a) Toyoura sand; and (b) granulated coal ash for input acceleration of 70% of reference motion

Next, the development of excess pore water pressure in both layers is examined for the case of input motion with 70% and 100% of the reference acceleration, and the time histories are shown in Figure 9. For both amplitudes of acceleration, Toyoura sand reached very high excess pore water pressure, although the generation of pore pressure was faster for the higher level of acceleration. For granulated coal ash, on the other hand, very high pore water pressures were obtained when the acceleration was 100% of the reference value, but a lower degree of pore pressure build-up can be seen when the amplitude was 70% of the reference value. The latter case indicated that liquefaction did not occur.

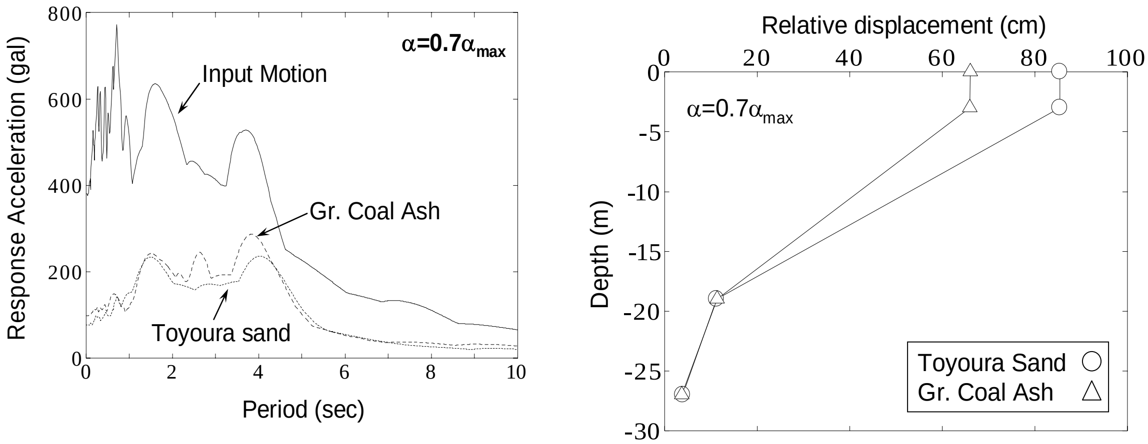


(a) (b)

Figure 9: Time histories of excess pore water pressure for Toyoura sand and granulated coal ash, with acceleration amplitude equal to (a) 100%; and (b) 70% of reference motion

The acceleration response spectrum of the input motion corresponding to 5% damping is compared with those obtained at the ground surface for both model grounds subjected to acceleration amplitude of 70% of the reference motion, and these are shown in Figure 10(a). It can be seen that the predominant period of the input motion is around 0.7 sec. In the case of Toyoura sand, liquefaction occurred at this level of acceleration and, as a result, the predominant period shifted to about 1.5 sec, indicating softening of the S_2 layer. On the other hand, the predominant period for granulated coal ash moved to about 4 sec. Although granulated coal ash did not undergo complete liquefaction, as indicated in Figure 9(b), the material softened to such a degree that the period has shifted to a higher level. Note that in both cases, the high frequency components of the base motion have been filtered through the softened grounds.

A comparison of the vertical distributions of the response displacement (relative to the base displacement) of Toyoura sand and granulated coal ash is shown in Figure 10(b), corresponding to an input motion with amplitude equal to 70% of the reference acceleration. It can be seen that, as expected, larger shear strain and therefore larger displacement occurred in S_2 layer consisting of Toyoura sand due to the complete liquefaction of the said layer. On the contrary, since the granulated coal ash did not completely liquefy, the relative displacement at the top was smaller when compared to Toyoura sand.



(a) (b)

Figure 10: Comparison of (a) acceleration response spectra; and (b) vertical distributions of response displacement for Toyoura sand and granulated coal ash for acceleration equal to 70% of reference motion.

Based on the above, it is can be said that the granulated coal ash would perform better as reclamation material than natural sands when subjected to the specified earthquake excitation. This is consistent with the findings made by Yoshimoto et al. (2006b) who observed that the liquefaction strength of granulated coal ash was about 1.7 times higher than that of natural sands, such as Toyoura sand. These confirm the effectiveness of granulated coal ash as backfill/reclamation material for use in waterfront areas.

5. CONCLUSIONS

Online pseudo-dynamic response tests were performed on model grounds consisting of Toyoura sand and granulated coal ash layers to investigate their seismic response behavior. Based on the results presented herein, the following are the major conclusions obtained.

1. The presence of granulated coal ash layer in the model ground resulted in shifting of the predominant period of the surface acceleration to a higher value, at least within the range of the amplitude of input acceleration investigated.
2. Granulated coal ash showed slower excess pore water pressure build-up when compared to natural sand for the same level of input motion.
3. Although the excess pore water pressure increased as the amplitude of the input acceleration increased, the response displacement of model ground with granulated coal ash layer was smaller when compared to that with Toyoura sand layer.

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