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Paper No. 1682. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

MODEL CENTRIFUGE TESTS ON LIQUEFACTION-INDUCED GROUND DISPLACEMENT

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ABSTRACT

This paper describes the results of model centrifuge tests in order to investigate the mechanism of liquefaction-induced ground displacement. From the results of the past shaking table tests under 1 g condition, it might be recognized that the completely liquefied soil behaved as a fluid at first, and then recovered its stiffness under large shear strain, namely 20～70 %, caused by ground displacement, which would propose the method of estimation of liquefaction-induced ground displacement quantitatively in the field. But generally sandy soil has the characteristics such that the stress-strain behavior of sandy soil depends on confining pressure acting on it. From the above reason, model centrifuge tests were conducted to investigate the influence of confining pressure on the behavior of liquefaction-induced ground flow. From the results of the centrifuge tests, it was recognized that the behavior of liquefied soil, namely vertical distribution of ground displacement, shape of ground surface after the test for example, was very similar to that of the test under 1 g condition and liquefied soil recovered its stiffness under large shear strain and it would have so-called critical shear strain. But the magnitude of critical shear strain could not be estimated quantitatively to unique value since the ground displacement depended on the duration of shaking the model ground.

KEY WORDS

Liquefaction; liquefaction-induced ground displacement; model centrifuge test; critical shear strain; recovery of stiffness of liquefied soil; vertical distribution of ground displacement; shape of ground surface; confining pressure; relative density; excess pore water pressure.

INTRODUCTION

At the time of 1983 Nihonkai-Chubu earthquake, liquefaction-induced large ground displacements with a magnitude of several meters, where the shear strain of liquefied soil sometimes reached several ten %, were for the first time measured on aerial photographs which were taken at the pre- and post-earthquake (Hamada *et al.*, 1986). Since then, case studies of past ten earthquakes in Japan, U.S. and Philippines have been conducted under a cooperation between Japanese and U.S. researchers (Hamada and O'Rourke, 1992). Based on the results from the case studies, influential factors for the magnitude of liquefaction-induced large ground displacement, such as ground surface gradient, thickness of liquefied soil for example, were examined, and empirical formulae for the prediction of the ground displacement were proposed (Hamada, 1986, Bartlett *et al.*, 1992).

One of research subjects on liquefaction-induced large ground displacement is to investigate the mechanism of the occurrence of the ground displacements with a magnitude of several meters, which were recognized even in almost flat surface ground with a gradient less than 1 %. Another research subject is to study the effect of large ground displacement on in-ground structures such as foundations and buried pipes.

Generally, there are in principle two kinds of manners to evaluate the behavior of the soil that constitutes liquefied ground which is deforming toward large ground displacement. The first is that the liquefied soil behaves as a fluid. The second is that it still behaves as a solid, but its stiffness is largely reduced due to the liquefaction. As a combination of the two, furthermore, a third manner is possible, where the liquefied soil behaves with dual phases of a liquid and a solid.

From the past shaking table tests under 1 g condition, it might be recognized that liquefied soil behaved as a fluid when it began to deform, and then it recovered its stiffness when its shear strain reached several ten % (Hamada *et al.*,1994). It is generally recognized that shear stress-strain characteristics of saturated sand depend on confining pressure acting on it under un-drained condition. The comparison of the test results concerning the behavior of liquefied soil under centrifugal condition with those under 1 g condition will be described in this paper.

OUTLINE OF RESULTS OF PAST SHAKING TABLE TESTS UNDER 1 G CONDITION

Past shaking table tests under 1 g condition were conducted by Hamada *et al.* in 1994. The outline of the test results were as follows:

Apparatus of the tests are shown in Fig. 1. The model ground of saturated sand with flat surface was made in a rigid soil box, and was shaken sinusoidally in the longitudinal direction of the box. After the model ground was completely liquefied, which was confirmed by pore water pressure meters in the model ground, the soil box was inclined by lifting one side of the box with a specific gradient.

The tests were conducted by varying the initial relative density of the model ground and the inclination gradient of ground surface. Figure 2 shows an example of the test results, when the initial relative density and the ground surface gradient are 41 % and 4.2 %, respectively. It was interesting to note that the initial inclination of the ground surface was preserved in the central part of the model ground even after the ground flow as shown in Fig. 2 (a). On the contrary, the ground surface became almost flat nearby the both sides of the soil box. Figure 2 (b) shows maximum ground displacements at three different elevations at five locations along the direction of the ground displacement. It was noteworthy that the vertical distribution curve of the ground displacement was like triangular in the central part of the model ground, where the initial inclination of the ground surface was preserved. On the other hand, those nearby the both sides of the soil box, where the ground surfaces became almost flat, were like parabolic.

The results indicate that the liquefied soil behaved as a fluid at first, but after a specific amount of the shear deformation of the ground soil, it recovered its stiffness and behaved as a solid body, when its shear strain reached so-called critical shear strain. Since in the central part of the ground, where the displacement was large, the shear strain of the liquefied soil reached critical shear one and the liquefied soil recovered its stiffness throughout the depth, the initial inclination of the ground surface was preserved and the distribution curve of the vertical displacement was like triangular. These results could be rationally explained by the following equation based on the volumetric transfer of the liquefied soil:

$$X=L-2H\sqrt{\gamma_c/\theta} \qquad (1)$$

where, X:preserved slope length, L:length of the model ground, H:thickness of the model ground, γ_c:critical shear strain, θ :initial gradient of the model ground surface

Furthermore, it was also indicated that the critical shear strain depended on the relative density of the liquefied soil, where the critical shear strain became small as the relative density increased.

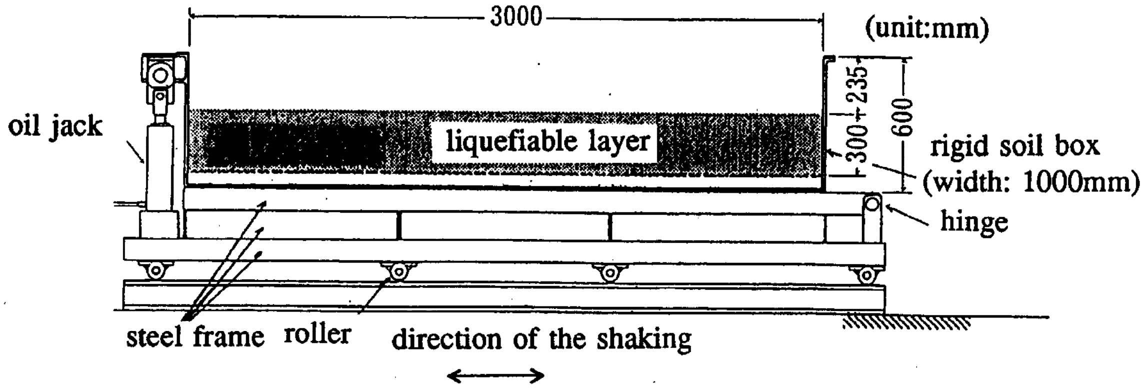
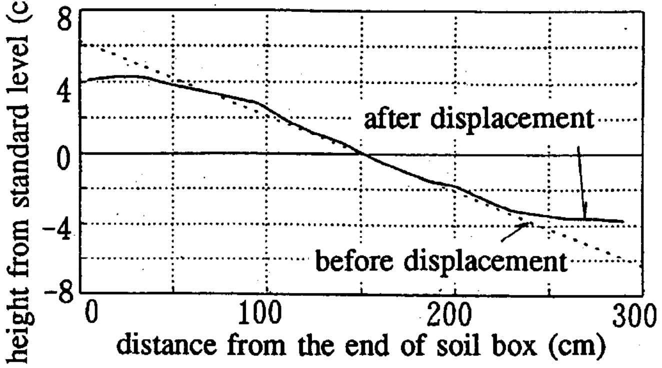
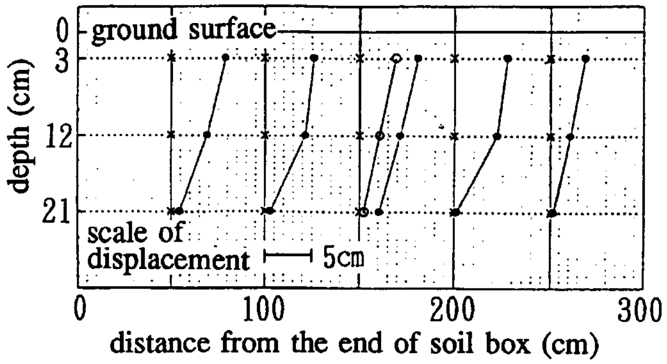


Fig. 1. Outline of apparatus for the test under 1 g condition.
(by Hamada *et al.*, 1994)



(a) Shapes of the ground surfaces



(b) Vertical distributions of maximum ground displacements

Fig. 2. An example of the test results under 1 g condition (Dr=41%, θ=4.2%).
(by Hamada *et al.*, 1994)

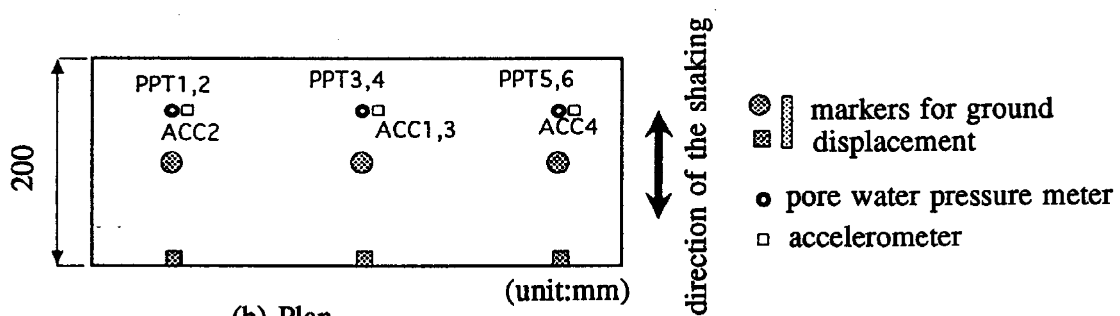
MODEL CENTRIFUGE TESTS

Methods of the Tests

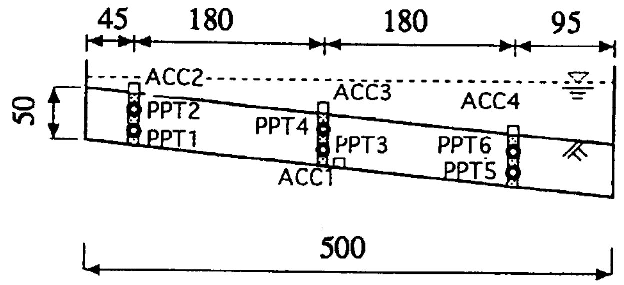
The tests were conducted with model ground of saturated Toyoura sand in silicone oil with a length of 50 cm, a width of 20 cm, a depth of 5 cm and a surface gradient of 5, 10 % in a rigid soil box, as shown in Fig. 3. The depth of model ground was small enough compared with the length in order to make large deformation of ground soil. Coefficient of viscosity of silicone oil was fifty times larger than that of water, which was determined by considering the consistency of similitude for dynamic phenomena and permeation phenomena. Liquefaction was induced by shaking the soil box and also induced was the ground flow by gravitational force due to the inclination of ground surface. The soil box was shaken sinusoidally by 20 g acceleration, 200 Hz under 50 g centrifugal condition in the direction perpendicular to the direction of ground flow, so that the effect of the inertia force acting on the flowing ground could be neglected. And shaking the model ground was conducted continually for two times in each case. As for the shaking duration, the first was for 0.05 seconds and the second was for 2 seconds, which was conducted after the dissipation of excess pore water pressure of the first shaking. As for the measurement of ground displacement, the maximum one was measured by the markers which were made of colored sand installed vertically in the model ground and the time history of the ground displacement was measured by a small-sized video camera whose sampling time was 1/30 second. Three cases of tests were conducted with two variable parameters, initial relative density and surface gradient of the model ground, as shown in Table 1.

Table 1. Parameters of model centrifuge test.

	Initial relative density (%)	Initial surface gradient (%)	Centrifugal acceleration (g)	Sinusoidal input wave	Relative density after first shaking (%)	Relative density after second shaking (%)
case 1	25	10	50	200Hz,20g	34	42
case 2	56	10	50		56	63
case 3	29	5	50		37	48



(b) Plan



(a) Side view

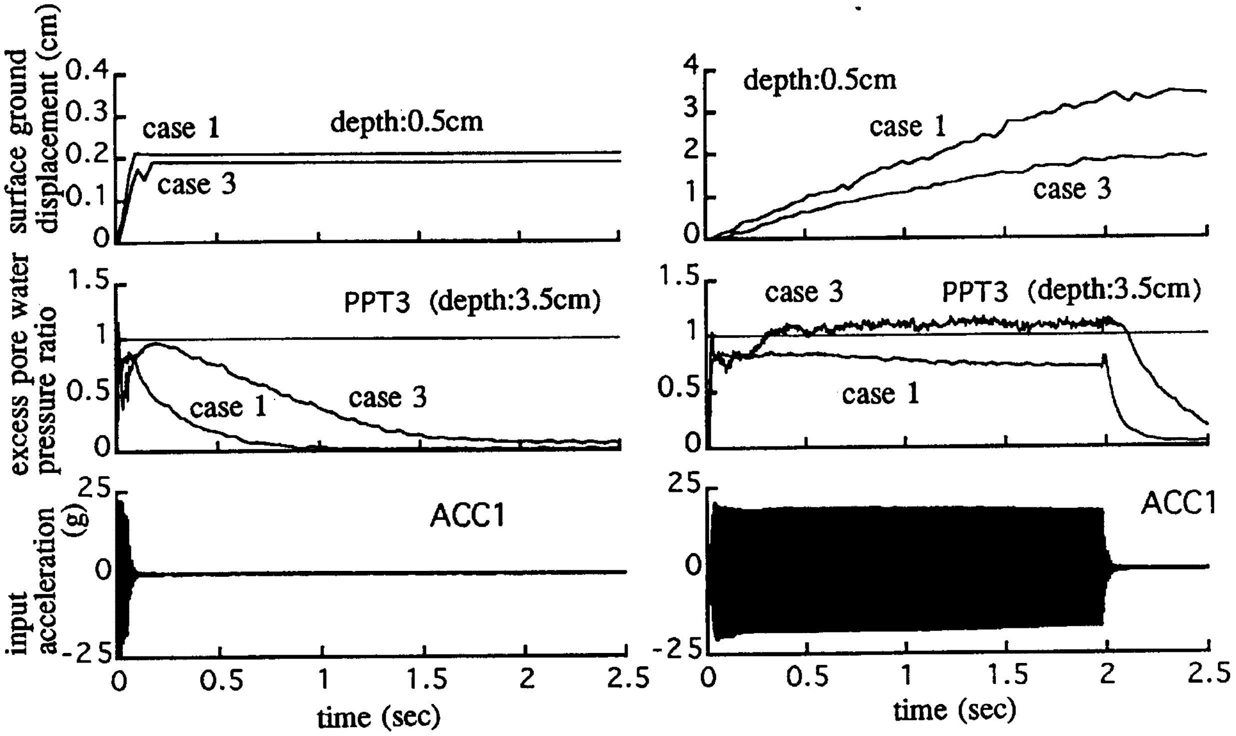
Fig. 3. Outline of model ground and instruments for the test under 1 g condition.

Results of the Tests

Surface Ground Displacement, Excess Pore Water Pressure Figure 4 shows examples of time histories of surface ground displacements and excess pore water pressure in case 1, 3, in which initial relative densities are almost the same, about 25 %, on the contrary initial surface gradients are different, 10 % and

5 %, respectively. The results of case 2 were spared in this paper since they were almost the same as those of case 1 except for the magnitude of the ground displacement. As for the ground displacement, it increased while shaking the ground was continued and stopped to increase when the shaking was stopped in each case. And the ground displacement was larger in case 1, namely in larger surface gradient case, than that in case 3 throughout the test. Small fluctuations of the ground displacement recognized in time histories were consequences of deviations during reading video camera records.

As for the excess pore water pressure, it suddenly increased and reached effective overburden pressure in each case, which means that the model ground was completely liquefied. And temporary decrease of excess pore water pressure recognized in early stage of the test was inferred to be consequences of suction around the pressure meter generated by the ground flow. After shaking the model ground, the excess pore water pressure decreased at a faster rate in case 1, namely in larger surface gradient case, than that in case 3 and also at a faster rate in the second shaking than that in the first shaking in each case.



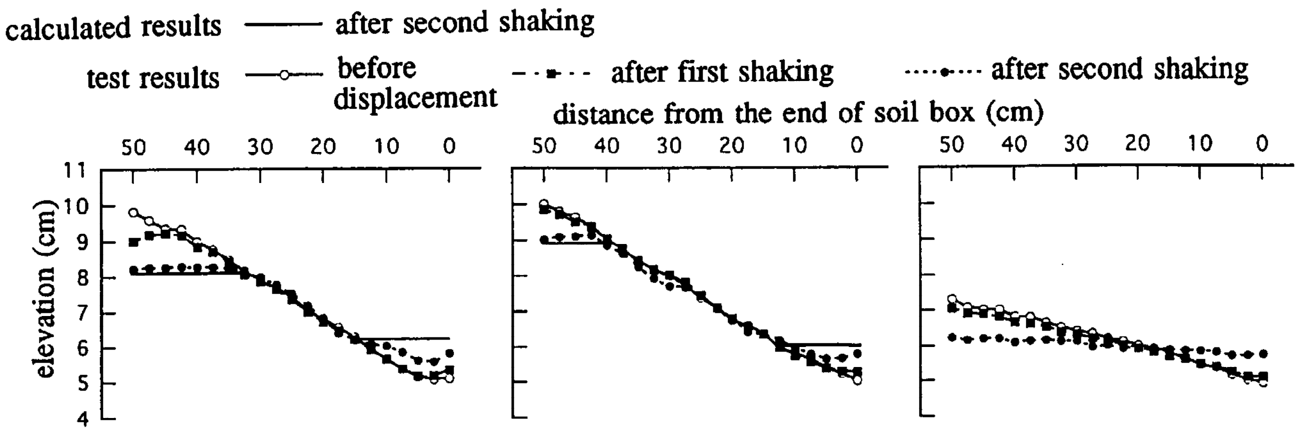
(a) First shaking case (b) Second shaking case

Fig. 4. Time histories of surface ground displacement, excess pore water pressure and input acceleration.

Shape of the Ground Surface after Shaking Figure 5 shows shapes of the ground surfaces before and after shaking in each case. It was recognized that the initial inclination of the ground surface was preserved in the central part of the model ground even after the ground flow and on the contrary the ground surface became almost flat nearby the both sides of the soil box in case 1, 2, in which the initial ground surface gradients were large. These results were as the same as for the tests under 1 g condition. And the preserved slope length of the ground surface became short in proportion to the shaking duration, in case 1, 2. On the other hand, in case 3, in which the initial surface gradient was small, the initial inclination of the ground surface was not preserved and the surface gradient became gradually small in proportion to the shaking duration.

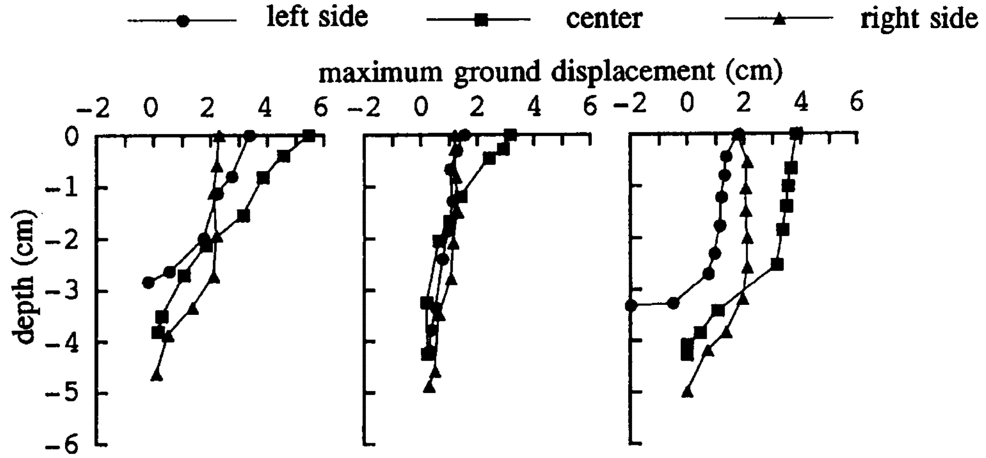
Vertical Distribution of the Ground Displacement Figure 6 shows vertical distributions of the maximum ground displacements after the tests at three locations along the direction of the ground displacement, namely nearby both sides of the soil box and central part of the model ground in each case, which were measured by the markers installed vertically beforehand at the central part of the model ground in the longitudinal direction, as shown in Fig 3. These locations corresponded to those of the almost flat ground surfaces and that of the preserved initial inclination, respectively in case 1, 2.

From these results, it was recognized that the vertical distribution curve of the ground displacement in the central part of the model ground was like triangular although those nearby the both sides of the soil box were like parabolic in case 1, 2. These results were as the same as for the tests under 1 g condition. On the other hand, in case 3 the distribution curves were like parabolic at any locations, and were not like triangular.



(a) case 1 (b) case 2 (c) case 3

Fig. 5. Shapes of ground surfaces.



(a) case 1 (b) case 2 (c) case 3

Fig. 6. Vertical distributions of maximum ground displacements.

Discussions In the centrifuge tests, the shapes of the ground surfaces calculated from equation (1), based on the test results under 1 g condition, were also shown in Fig. 5 using the critical shear strains, which were calculated from the vertical distributions of the ground displacement in the central part of the ground in Fig. 6 (a), (b). It was noteworthy that calculated ground surfaces well coincided with those of test results. And the preserved slope length of the ground surface was longer in case 2, namely in larger relative density case, than that in case 1, namely in smaller relative density case. These results well coincided with test results under 1 g condition. On the other hand, in case 3, since the vertical distribution curve was not like triangular even in the central part and initial inclination of ground surface was not preserved, the shear strain of liquefied soil would not reach critical shear one even after the ground flow because of small ground displacement. If equation (1) could be applied to test results in case 3 using the supposed critical shear strain which was calculated from deep part of the vertical distribution of the ground displacement in Fig. 6 (c), calculated value of preserved slope length of ground surface became negative. This also coincided with test result. Thus the behaviors of liquefied soil under centrifugal condition were very similar to those under 1 g condition, which means that liquefied soil would recover its stiffness under large deformation and have the critical shear strain under centrifugal condition as the same as for the test under 1 g condition.

But as for the magnitude of the critical shear strain of liquefied soil, it could not be estimated to unique value quantitatively from the test results since the ground displacement depended on the duration of shaking the model ground, although it could be estimated quantitatively from the relative density of the soil under 1 g condition as mentioned before. When the ground displacement was naturally induced by gravitational force of surface inclination as in centrifuge test, as the same manner as for the field, it stopped at the end of shaking the model ground and the shear strain was small, for example several % in the first shaking. However, the ground displacement artificially induced by lifting one side of the soil box as in 1 g condition test was large and the shear strain reached several ten %, which corresponded with actual phenomena observed in the past earthquakes. It was an urgent problem to make clear the reason why the ground displacement stopped at the end of shaking and actual phenomena observed in the past earthquakes could not be realized in such laboratory tests in order to investigate the mechanism of liquefaction-induced ground displacement.

As for the excess pore water pressure after shaking the model ground, it dissipated at a faster rate in case 1 than that in case 3 and also at a faster rate in the second shaking than that in the first shaking in each case, as mentioned before. From these results it was inferred such that the dissipation rate of excess pore water pressure of liquefied soil after ground flow would depend on the magnitude of shear strain of the soil since the ground displacement was larger in case 1 than that in case 3, and also larger in the second shaking than that in the first shaking in each case.

CONCLUSIONS

Model centrifuge tests were conducted concerning the results of past shaking table tests under 1 g condition, where liquefied soil recovered its stiffness when its shear strain reached so-called critical shear strain, several ten %, due to liquefaction-induced ground displacement. From the results of the centrifuge tests, it was recognized that (1) liquefied soil recovered its stiffness as the same as for the test under 1 g condition, (2) but the magnitude of the critical shear strain could not be estimated to unique value quantitatively from the test results since the ground displacement depended on the duration of shaking the model ground. It was an urgent problem to make clear the reason why the ground displacement induced by gravitational force of surface inclination stopped at the end of shaking and actual phenomena observed in the past earthquakes could not be realized in such laboratory tests in order to investigate the mechanism of liquefaction-induced ground displacement and to estimate quantitatively the magnitude of the ground displacement in the field.

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