Liquefaction damage enhanced by interference between the body wave and surface wave induced from the inclined bedrock

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ABSTRACT

One of the important characteristics of the liquefaction damage observed at Urayasu city during the Great East Japan Earthquake is that liquefied and non-liquefied site was inhomogeneously distributed. The difference in damage levels has often been explained by the presence/absence of past ground improvement and by the difference in the dates of reclamation work. Such causes of extensive damage are, no doubt, correct. However, sufficient explanations have not been provided yet concerning the mechanism of liquefaction occurrence in ground with large fine fraction content and the reason why the liquefaction damage was non-uniform. In this study, seismic response analysis with multi layered system was employed paying special attention to the stratum organization at the deeper part of the subsurface liquefiable layer. Analysis result showed that, in addition to characteristic of the earthquake motion and inhomogeneity of the ground itself, irregularly shaped stratum organization of Urayasu city was one of the important factor for extensive and non-uniform liquefaction damage.

Keywords: liquefaction, irregularly formed stratum organization, surface wave

1. INTRODUCTION

The Great East Japan Earthquake Disaster caused liquefaction damage to wide areas in Urayasu City. The distinctive characteristics of the damage caused were as follows. 1) Although the area affected was about 400 km away from the epicenter and the seismic intensity was only about 5 (maximum acceleration of 100 to 200 gal in surrounding locations according to the K-net and other ground surface measurement records), liquefaction damage was very severe. 2) The particle size characteristics of jetted sand samples taken in the vicinity of the liquefied areas showed the amount of fine fraction to be large, although it had been considered hitherto that grounds with large fine fraction content are not easily liquefied. 3) Liquefied areas and areas where no liquefaction occurred were distributed over the whole region in a nonuniform manner. The damage was concentrated in relatively new reclaimed lands in a region between the city center and the southeast part, but almost no damage occurred in the older land in the northwest part as seen in Figure 1. 4) The extent of liquefaction damage was aggravated by the aftershock that occurred just 29 minutes after the main tremor. The reason for 1) and 2) above has been attributed to the long duration of continuity of the tremors, while 3) has been explained by the nonuniformity of the geomaterials and ground conditions caused by factors such as the differences in the dates of reclamation and the execution/non-execution of land improvement measures in the past.

The cross-sectional geological profile at Urayasu City along the survey line X–Y in Figure 1 is illustrated in Figure 2, which indicates that the bedrock slopes down sharply from X (landside) to Y (seaside). Considering this ground layer structure in conjunction with the damage distribution shown in Figure 1, it can be said that the liquefaction damage was light on the landside where the soft clay layer was thin but severe on the ground immediately above the bedrock slope and on the seaside where the soft clay layer was thick.

The reasons for the severe and nonuniform liquefaction damage that occurred is investigated in this paper by focusing on the irregular ground layer structure at Urayasu City (the bedrock surface sloping down from the landside toward the seaside and the difference in the thicknesses of the weak clay layer above the bedrock as a result of the slope) through seismic response analyses of a multilayer ground system. It is demonstrated that in addition to the reasons given in the past such as characteristics of the seismic motion and the nonuniformity that already existed in the ground, the extent of liquefaction damage was aggravated by the distinctive ground layer structure at Urayasu City. This investigation showed that 1) the
2 ANALYSIS CONDITION

The ground model shown in Figure 3 was prepared in order to obtain a clear understanding of the effects of the sloped bedrock and the resulting variation in soft clay layer thickness, which are distinctive features of the ground at Urayasu City. The effect of the thickness of the soft clay layer is investigated in Section 3 below using the vertical one-dimensional model shown in Figure 3 and by calculating the seismic response at locations a, b, and c shown in the same figure. The effect of the sloped bedrock is studied in Section 4 using a two-dimensional model. The material constants of each layer were determined from boring surveys performed at Urayasu City and by using the SYS Cam-clay model to simulate the various mechanical tests on undisturbed soil specimens sampled from the same locations. As for the initial values, it was assumed that the specific volume (density), degree of structure, stress ratio, and anisotropy were uniform in the depth direction. The overconsolidation ratio was assigned according to the overburden pressure. The list of elasto-plastic conditions is shown in Table 1. Please note that although the actual surface ground layer is inhomogeneous due to the effects of the reclamation work that was done at different periods and the effects of past ground improvement work, it is assumed here that the liquefied surface layer is a horizontal one in a homogeneous state in order to determine the effect of irregular ground layers on liquefaction damage. The hydraulic boundary was set so that the ground surface coincided with the water level with the water pressure at zero. The bottom face and the two lateral faces were assumed to be undrained boundaries. The seismic wave that was input is shown in Figure 4. The seismic wave

thick weak clay deposit amplifies the seismic wave in the somewhat long-period range, which results in large shear deformation and increased risk of liquefaction; 2) surface waves are induced continuously from the edge of the sloped bedrock even after the main shock has ended, causing occurrence of a continued “post-motion phenomenon” that enhances liquefaction; and 3) the complex interference between the surface wave and the body wave from the bottom causes the ground surface deformation to become nonuniform even if the condition of the ground is assumed to be homogeneous. The analysis code used here is the soil-water coupled finite deformation analysis code GEOASIA mounted with the elasto-plastic constitutive equation (SYS Cam-clay model) capable of describing soils ranging from sand to intermediate soil and clay.
that was observed at a depth of about G.L. -36 m at the Shinagawa observation point of the Tokyo Bureau of Port and Harbor was input as a 2E wave in the horizontal direction equally to all nodes at the bottom face of the ground. In addition to establishing lateral boundary element simple shear deformation boundaries at the two lateral ends of the boundaries during the earthquake, a viscous boundary equivalent to $V_s=400$ m/s was set up at the bottom face of the ground.

3 EFFECT OF THE WEAK CLAY LAYER THAT EXISTS BENEATH THE LIQUEFIED LAYER (1-DIMENSIONAL ANALYSIS)

Figure 5 depicts the acceleration responses of the ground surface at locations $a$, $b$, and $c$ obtained through the one-dimensional analysis. There are no significant differences in the maximum acceleration at the three locations. However, the Fourier amplitude spectra show that the seismic wave was amplified at around 0.7 s at location $a$, 1.4 s at location $b$, and 2.0 s at location $c$, which indicates that as the clay layer becomes thicker, the amplification of the seismic wave shifts towards somewhat longer periods. Figure 6 shows the mean effective stress reduction ratio at the central part of the sandy layer. The stress reduction ratio increased rapidly when the main tremor occurred (at around 100 s after commencement of the earthquake) but reached a nearly steady state when the tremors ceased after about 200 s. This indicates that in the case of one-dimensional analysis, the state of liquefaction has not yet been reached at any of the locations. However, at locations $b$ and $c$, where the weak clay layer is thicker, the mean effective stress reduction ratio is greater than at location $a$. This indicates that locations $b$ and $c$ are closer to liquefaction than location $a$. Even if there is no significant difference in the maximum acceleration,

amplification of the long period components of acceleration leads to the occurrence of large shear deformations at the ground surface. As a consequence, even intermediate soils, which are not easily liquefied, come somewhat close to reaching the state of liquefaction.

4 EFFECT OF BEDROCK SLOPE (2-DIMENSIONAL ANALYSIS)

Figure 7 illustrates the acceleration responses of the ground surface at locations $a$, $b$, and $c$ obtained through two-dimensional analysis. Comparison with Figure 5 shows that there is no major difference in the response at location $a$. At locations $b$ and $c$, however, the maximum acceleration has become greater, and relatively large tremors continue even after the main

| Elasto-plastic parameters | SAND | CLAY | BEDROCK |
|---------------------------|------|------|---------|
| Critical state index $M$ | 1.40 | 1.40 | 1.50    |
| NCL intercept $N$         | 2.00 | 3.02 | 2.00    |
| Compression index $\lambda$ | 0.10 | 0.242| 0.005 |
| Swelling index $\kappa$  | 0.0025 | 0.020 | 0.0005 |
| Poisson's ratio $\nu$    | 0.10 | 0.10 | 0.10    |
| Evolution parameters     |      |      |         |
| Degradation index of structure $\beta$ | 8.00 | 0.65 | 0.05 |
| Ratio of $\beta / \kappa$ | 1.00 | 0.40 | 0.50 |
| Degradation index of overconsolidation $\mu$ | 8.00 | 20.0 | 0.3 |
| Rotational hardening index $\nu$ | 10.0 | 0.20 | 0.20 |
| Soil particle density $\rho_s$ (g/cm$^3$) | 2.787 | 2.690 | 2.650 |
| Mass permeability index $k$ (cm/s) | $1.0 \times 10^6$ | $1.0 \times 10^3$ | $1.0 \times 10^7$ |
| Initial conditions       |      |      |         |
| Specific volume $v_s$    | 1.900 | 3.350 | 2.110 |
| Stress ratio $\sigma_r$ | 0.545 | 0.545 | 0.545 |
| Degree of structure $\nu$ | 3.04 | 21.75 | 100 |
| Overconsolidation ratio $\rho_s$ | distributed | distributed | distributed |
| Degree of anisotropy $\kappa_0$ | 1.00 | 0.75 | 0.40 |

Table 1. Elasto-plastic characteristics used for the analysis
tremor has ended. Figure 8 shows the mean effective stress reduction ratio at the central part of the sandy layer. It can be seen that at locations \(b\) and \(c\), where no liquefaction occurred in the case of the one-dimensional analysis, the increase in stress reduction ratio occurs earlier, continues gradually even beyond 200 s at which time the main tremor has ended, and finally reaches the stage of liquefaction. The reason for this phenomenon can be explained by referring to Figure 9, which depicts the velocity vector distribution 60 seconds after commencement of the earthquake. Generation of secondary waves\(^6\) that seem to be rolling up in the counterclockwise direction can be noticed in parts of the ground surface. These surface waves are created at the edge of the bedrock slope and propagate toward the right side of the figure. Although the data is not shown in this paper, no such surface waves were created in the case of horizontally layered grounds. The surface waves were created by reflection and refraction of the body wave in the plane of material discontinuity between the bedrock and the clay layer. In other words, the two-dimensional analysis shows that generation of the secondary waves results in the accelerations becoming greater and lead to a “post-motion phenomenon” of relatively large continued tremors occurring even after the main tremor has ended and thus aggravating the extent of liquefaction damage.

The shear strain distributions 100, 200, and 300 s after earthquake commencement are illustrated in Figure 10. Although a homogeneous ground state has been assumed, the strains generated are nonuniform over the entire area and are particularly large directly above the sloped part. Figure 11 shows the amount of
settlement occurring if consolidation is allowed to occur over a 30-year period after the earthquake. As in the case of the shear strain distribution during the earthquake, the amount of settlement is uneven, and the settlement of the sandy layer is large from directly above the slope towards the sea. As was shown in Section 3, body waves with different dominant periodic bands rise upward depending on the thickness of the soft clay layer. Interference between such body waves and the surface waves in a discontinuous manner causes localized ground deformation and aggravated liquefaction damage. This shows that the deformation of the ground surface varies widely even if homogeneity of the ground materials and ground conditions is assumed. This is believed to be similar to the “Earthquake Damage Band7)” phenomenon that was observed in the Southern Hyogo Prefecture Earthquake.

5 EFFECTS OF BEDROCK SLOPE AND BASIN TOPOGRAPHY

Analysis of the ground behavior was carried out assuming the bedrock at the central part of Figure 3 to have a small slope of 1 degree. The velocity vector distribution 60 s after and the shear strain distribution 200 s after the commencement of the earthquake are shown in Figures 12 and 13, respectively. It can be seen that if the slope of the bedrock is small, clearly defined surface waves do not appear and that the vertical upward components are small. When compared to the case of the bedrock slope being 3 degrees, the shear strains are smaller overall and there is no clear evidence of nonuniformity.

Analysis was also carried out assuming the bedrock topography to be a basin with a 3-degree slope. The velocity vector distribution 60 s after and the shear strain distribution 200 s after the commencement of the earthquake are shown in Figures 14 and 15, respectively. The velocity vector diagram shows the surface waves that originated and propagated from the left and right sides of the basin and collided at various locations directly above the basin trough. It is clear from Figure 15 that the repeated surface wave collisions directly above the basin trough produce markedly more shear strain localization and nonuniformity. Figure 16 shows the acceleration responses of the basin and inclined grounds, both with 3-degree slopes. The one-dimensional layer structures of the two grounds in the vertical direction are the same at the point of analysis. Comparison of the accelerations shows that although the layer structure is the same, the maximum acceleration is greater in the case of the ground with basin topography. As was shown in Figure 14, the surface waves originating from the two ends of the basin collide just at the center of the basin and cause the tremors to become larger. After the Mexico Earthquake (1985), it has been pointed out that the extent of earthquake damage could be aggravated in grounds with basin topography8). There are reports stating that at Urayasu City too, the existence of localized areas with basin topography actually aggravated the extent of liquefaction damage.
6 CONCLUSION

The extensive liquefaction damage seen in the Great East Japan Earthquake Disaster is often attributed to the long period over which the tremors continued and to the nonuniformity of the geomaterials and ground conditions caused by factors such as the differences in the dates of reclamation and the execution/non-execution of land improvement measures in the past. In this work, it is demonstrated through numerical analyses that the extent of liquefaction damage was aggravated by the distinctive ground layer structure at Urayasu City in addition to other causes such as the characteristics of the seismic motion and the nonuniformity that already existed in the ground. Although omitted here due to space limitations, investigation of the effect of aftershocks showed that the relatively large aftershock that occurred just 29 minutes after the main one also aggravated the liquefaction damage. Moreover, it was confirmed through analysis that if the above aftershock had occurred a day later, it would not have produced further liquefaction damage because the excess pore water pressure would have dissipated to a certain extent during that one day interval.

Irregular ground boundaries such as those in inclined grounds or basin grounds are not restricted to Urayasu City only and could exist anywhere. The Nobi Plain, which has a high risk of liquefaction occurrence, actually has a slightly sloping bedrock similar to the one at Urayasu City and also contains many areas with basin topography9). Conventional methods such as the “Simplified Method” or the “FL Method” are based on microtopographical classification and take only the “soil properties” of the surface layer into consideration when evaluating liquefaction occurrence without directly taking into account the effects of earthquake duration, layer structure of the ground in the depth direction, irregular boundaries, etc. The authors plan to study the effects of these factors too in the future in preparation for a huge Nankai Trough Earthquake.

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