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LOCALIZED/ENORMOUS SEISMIC DAMAGE OF SUBSURFACE GROUND INDUCED BY THE STRATUM IRREGULARITY

K. Nakai(1), T. Noda(2), S. Fukuda(3), H. Murao(4), A. Asaoka(5)

(1) *Associate Professor, Nagoya University, nakai@civil.nagoya-u.ac.jp*
(2) *Professor, Nagoya University, noda@nagoya-u.ac.jp*
(3) *Mc. Student, Nagoya University, fukuda.shinya@d.mbox.nagoya-u.ac.jp*
(4) *Murao Chiken Corporation, h-murao@pearl.ocn.ne.jp*
(5) *Senior Research Advisor, Association for the Development of Earthquake Prediction, asaoka@8f.adep.or.jp*

Abstract

In the past seismic damages, there have been many reports of seismic damages which were localized and enlarged due to stratum irregularity. However, because the current seismic response/damage of subsurface ground is generally predicted based on a vertical one-dimensional model, multi-dimensional effects such as generation of surface waves, and complex interference between surface waves and body waves are not taken into account. Therefore, underestimation and oversight of seismic damage might be feared.

During the Kumamoto earthquake in 2016, graben collapse occurred in the Aso Caldera in a strip shape. In this paper, the influence of stratum irregularity of Caldera on the seismic damage was examined by seismic response analysis using a two-dimensional elasto-plastic model. The analysis code employed in this study was the soil-water coupled finite deformation analysis code GEOASIA, which incorporates SYS Cam-clay model that allows description of the behavior of soils ranging from sand through intermediate soils to clay within the same theoretical framework. As a result of the analysis, the following ground motion characteristics were confirmed due to the stratum irregularity. It is thought that these characteristics overlapped and caused the localized graben collapse in the Aso Caldera.

1. The "lens effect" was observed in which body waves were refracted at the boundary between the basement and the sedimentary layer and concentrated at a specific location.
2. Surface waves were generated at the edge of the irregular base that was exposed on/near the ground surface. The "edge effect" in which body waves and surface waves interfered with each other was observed.
3. In the basin topography, the surface waves repeatedly reflected at the edge and stay in the basin for a long time.
4. When soft clayey soil is thick like Aso Caldera, the long period component would be amplified since the natural period of the ground is large. If the ground is disturbed by strong motion and loses its rigidity, the natural period further would increase and the long period ground motion would become even more prominent in the surface.

There are numerous of stratum irregularity all over the world. This analysis results suggest that for precise seismic damage prediction, it is important to validate by multi-dimensional elasto-plastic seismic response analysis after grasping the effects of stratum irregularity.

1) Noda, T. et al.: Soil-water coupled finite deformation analysis based on a rate-type …, *S&F*, **48**(6), 771-790, 2008.
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Keywords: seismic response analysis, stratum irregularity, surface waves, long-period ground motion, soft clay

1. Introduction

Due to the 2016 Kumamoto Earthquake, a subsidence crack (graben-like crack) appeared intermittently in the northwestern part of the Aso Caldera. These occurred locally at a point approximately 30 km away from the epicenter after the magnitude 7.3 earthquake that occurred at 1:25 am on April 16th. It was thought that the Hinagu-Futagawa fault zone that triggered the Kumamoto earthquake did not reach into the Aso Caldera, and both fault zone are strike-slip fault zones, whereas the subsidence cracks generated at Aso Caldera are normal fault-like. Therefore, there is no direct causal relationship between the subsidence cracks and the Hinagu-Futagawa fault zone. Various causes have been considered so far. However, the precise cause for such extensive seismic damage has not yet been identified. In order to elucidate the mechanism of this Aso Caldera's collapse damage, the effects of the irregular basin topography of the Caldera on the seismic damage of the surface layer were numerically examined. The analysis code employed in this study was the soil-water coupled finite deformation analysis code ***GEOASIA*** [1], which incorporates SYS Cam-clay model [2] that allows description of the behavior of soils ranging from sand through intermediate soils to clay within the same theoretical framework.

2. Analysis model and conditions

Aso Caldera forms an irregular stratum with thickly deposited volcanic ash clay in the basin. The analytical model shown in Figure 1 was prepared in a two-dimensional plane strain condition based on the S-wave velocity distribution obtained by boring survey [3] and microtremor exploration [4] performed in the Matoishi area where the collapse damage was appeared. Since the S-wave velocity distribution was obtained only on the outer ring mountain side, the asymmetric basement slope was assumed in Aso Caldera, considering that the gradient of the inner ring mountain is larger than that of the outer ring mountain. In addition, by reproducing the results of standard consolidation tests and undrained shear tests using undisturbed samples collected from the site by using the SYS Cam-clay model, the elasto-plastic properties (initial conditions, elasto-plastic parameters and evolutional parameters) of soil in the Aso Caldera were determined. The sedimentary layer was divided into three layers, all of which are clayey soils. The shallow and the middle parts are silty clay having high water content (high void ratio) within a sensitive condition. The deeper part has a large amount of clay, and has lower water content (smaller void ratio) compared with the shallow and middle parts. The input ground motion used in the analysis is an observed strong motion at Kik-net station Mashiki. A viscous boundary [5] equivalent to V_s = 700 m/s was assumed in the horizontal direction on all nodes of the bottom face, and the seismic waveform was input in the horizontal direction equally on all nodes of the bottom face of the ground.

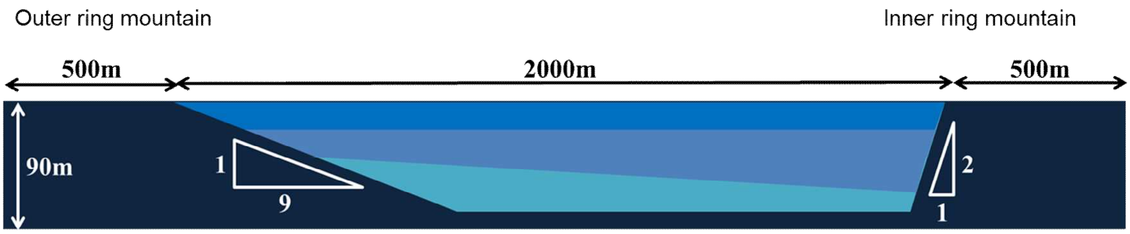

Fig. 1 Analytical model

3. Analysis results

3.1 Velocity vector

The velocity vector distribution is shown in order to grasp the state of the wave propagation occurring in the irregularly shaped ground. Figure 2 shows the velocity vector 7.5 seconds after the occurrence of the earthquake for the entire analysis region. Figure 3 shows the velocity vector 11 seconds after the occurrence of the earthquake with the ground surface near the inclined bedrock portion enlarged. The color of the vector corresponds to the magnitude, red means upward and blue means downward. From Fig. 2, it can be seen that the body waves propagated from the deeper part to the shallower part, and also refracted and propagated at the boundary between the base and the deposited layer (so called as “lens effect”). From Fig. 3, near the ground surface at the end of the basin, an arc-shaped wave (surface wave: Rayleigh wave for two-dimensional plane strain analysis) that rotated in the opposite direction to the traveling direction were excited at the edge of the bedrock, and propagated to the central part. As described above, in the case of an irregular geological structure, it can be understood that wave propagation such as refraction of a body wave and excitation and propagation of a surface wave became extremely complicated. Furthermore, body waves and surface waves showed complex interference near the ground surface. Although illustration is omitted, surface waves repeated reflections in the basin, so they continued to stay even after the end of the earthquake and the ground surface shook for a long time.

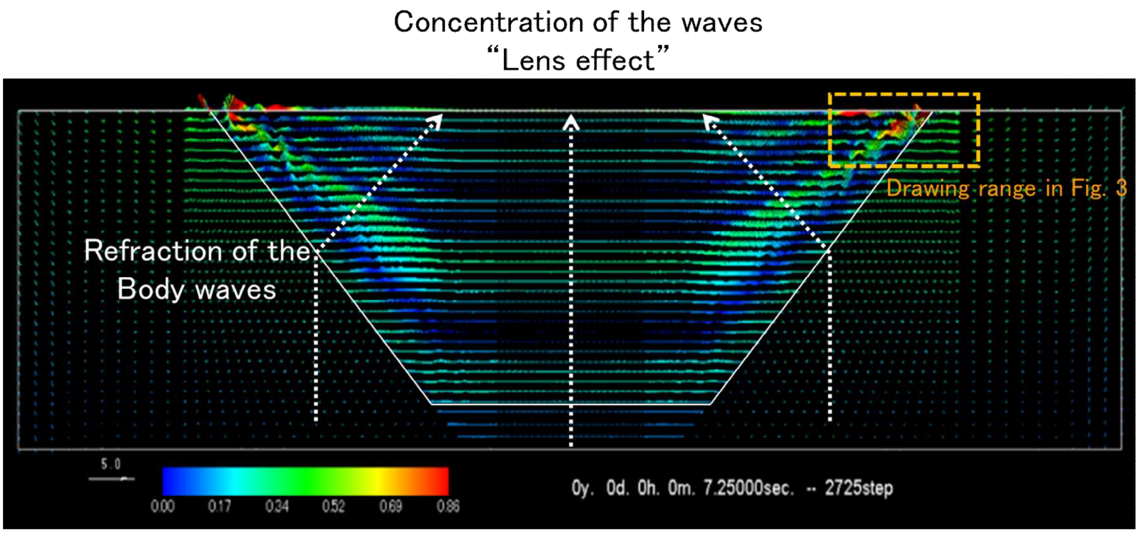

Fig. 2 Velocity vector distribution 7.5 s after the occurrence of the earthquake (entire analysis region)

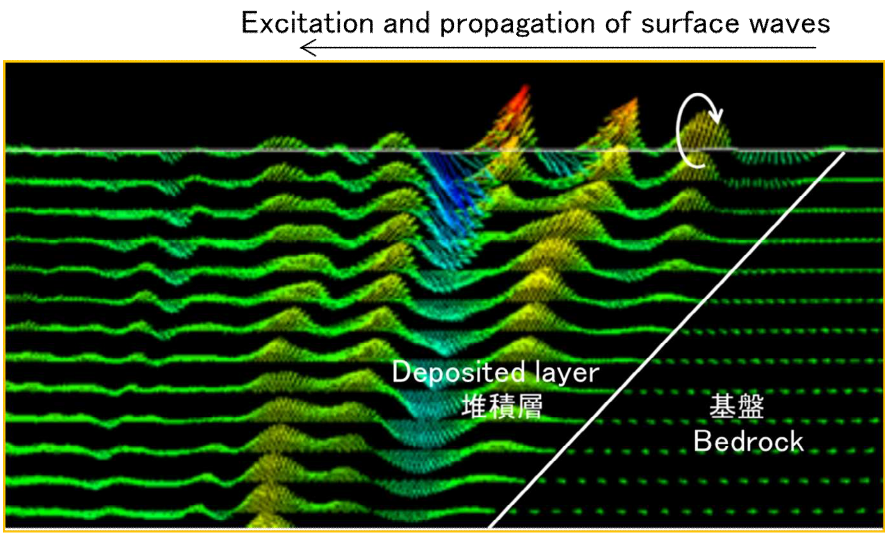

Fig. 3 Velocity vector distribution 11 s after the occurrence of the earthquake (near the inclined bedrock)

3.2 Fourier spectrum of velocity response

A one-dimensional model of the same stratum composition as the central part of the ground was prepared and compared with the two-dimensional analysis results in order to understand the difference of the shaking occurring on the ground surface. Figure 4 shows the Fourier amplitude spectrum of the velocity response on the ground surface in the central basin for 250 seconds after the end of the earthquake. First, we analyze from the one-dimensional analysis results. The soft volcanic ashy clayey soil is thickly deposited in the Aso Caldera. As a result, in addition to the inherently long natural period, the ground was disturbed during the earthquake and the rigidity was lost, so the natural period was further increased, and predominant periods were observed around 7.0 and 3.3 seconds. Long-period surface waves were excited in the case of two-dimensional analysis considering stratum irregularities. Amplified interference with a long-period body wave caused complicated wave propagation to significantly disturb the ground. Therefore, long-period shaking became more prominent than one-dimensional analysis.

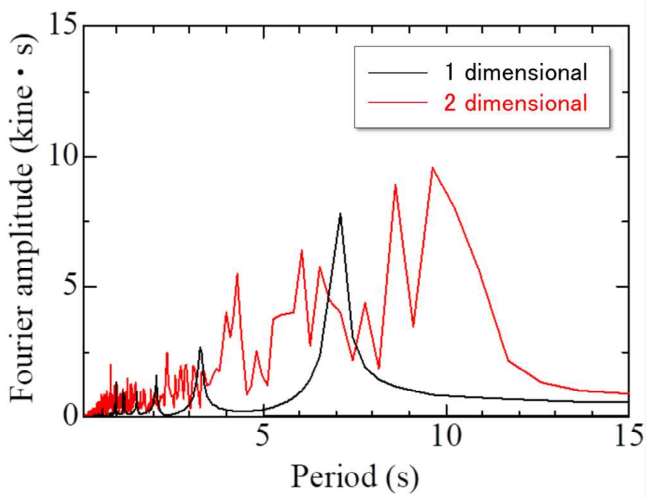

Fig. 4 Fourier amplitude spectrum of the velocity response

3.3 Change of mean effective stress over time

Figures 5 and 6 show the distribution of the mean effective stress reduction ratio immediately after the earthquake (40 seconds after the occurrence of earthquake), and 10 minutes after the earthquake, respectively. The figure is enlarged 8 times in the vertical direction for clarity. This index shows how much the effective stress has decreased with respect to the initial effective stress. If the effective stress decreases, this index will increase from 0 to 1. And 1 means that the effective stress becomes zero, which indicates that the rigidity of the ground is fully lost like liquefaction condition. As shown in Fig. 5, mean effective stress of the sedimentary layer in the Aso Caldera decreased during the earthquake, even on clayey soil. In addition, since surface waves stayed in the Caldera basin, the mean effective stress continued to decrease even after the end of seismic motion (Fig. 6). The clayey ground has been originally said to be "insensitive" to the earthquake, but the clayey soil of Aso Caldera is a soft volcanic ash soil with high water content. For this reason, it can be seen that the mean effective stress (stiffness) was reduced due to the disturbance caused by the large shaking.

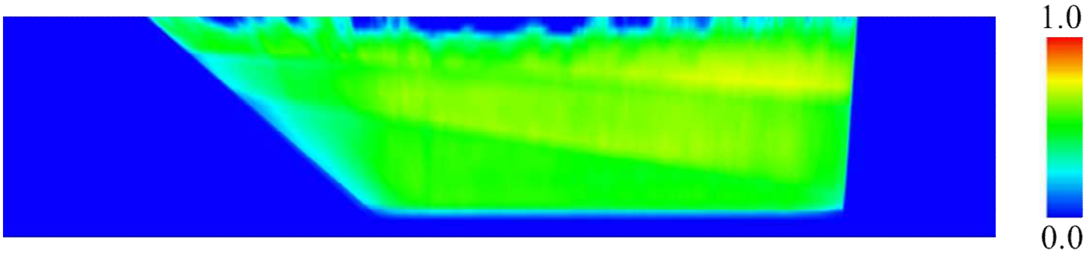

Fig. 5 Mean effective stress reduction ratio immediately after the occurrence of an earthquake

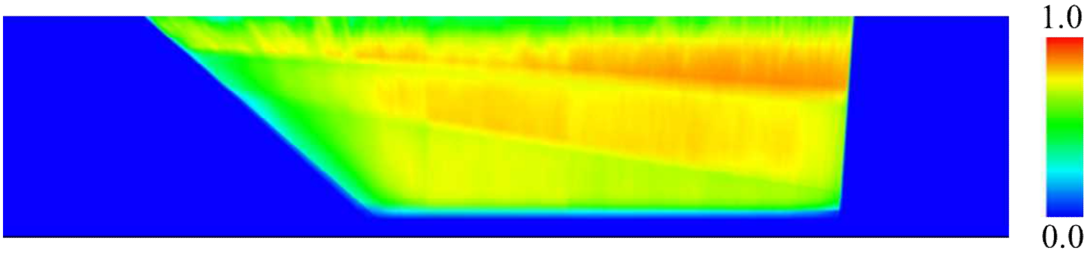

Fig. 6 Mean effective stress reduction ratio 10 min after the occurrence of an earthquake

3.4 Change of shear strain over time

Figures 7 and 8 show the distribution of the shear strain immediately after the earthquake (40 seconds after the occurrence of earthquake), and 10 years after the earthquake, respectively. The figure is enlarged 8 times in the vertical direction for clarity. From Fig. 7, it can be confirmed that a large shear strain generated locally on the ground surface near the outer ring mountain (left side of the figure) immediately after the end of the earthquake, which is similar to the actual collapse damage at Aso Caldera. This is because the body waves and the surface waves propagated from the deep part interfered with each other at a specific position (so called as “edge effect”), and the clayey soil was remarkably disturbed by large shaking. Referring to Fig. 8, the shear strain increased at the boundary between the second and third layers of the deposited layer. As can be seen from Fig. 6, even in the clayey ground, the mean effective stress was greatly reduced during the earthquake due to the soft and sensitive condition. With the recovery of the effective stress reduced during the earthquake, consolidation deformation occurred after the earthquake. Because of the low permeability of clayey soil, the analysis results suggest that ground deformation may have taken place in the deeper part of the sedimentary layer in the future.

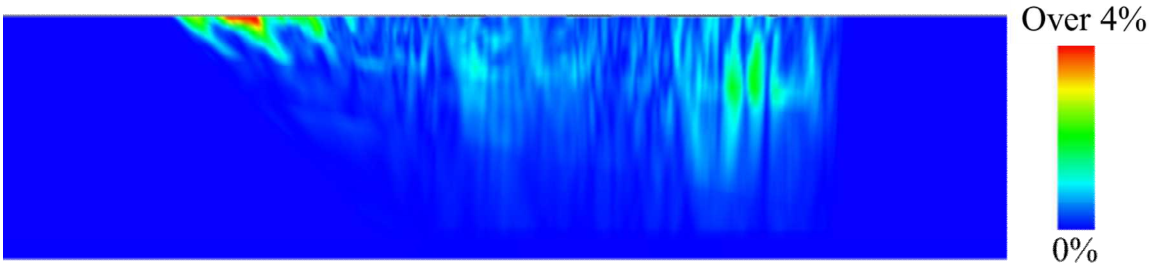

Fig. 7 Shear strain distribution immediately after the occurrence of an earthquake

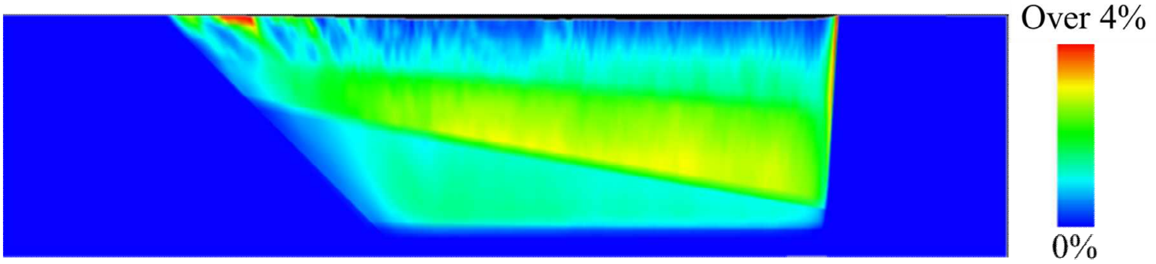

Fig. 8 Shear strain distribution 10 years after the occurrence of an earthquake

4. Conclusions

In this paper, we conducted a soil-water coupled seismic response analysis using a two-dimensional elasto-plastic model to clarify the mechanism of the subsidence crack (graben-like crack) damage of the Aso Caldera caused by the 2016 Kumamoto earthquake. The effects of the irregular basin topography of the Caldera on the seismic damage of the surface ground were investigated. As a result, the following ground motion characteristics were confirmed in terms of the irregularity of the stratum.

1) Body waves were refracted at the boundary between the basement and the sedimentary layer which would concentrate at a certain point ("lens effect").

2) Surface waves were excited at the boundary between the basement and the sedimentary layer on the ground surface. And the body waves and the surface waves, or the surface waves itself caused amplifying interference ("edge effect").

3) In the basin terrain, the surface wave repeated reflection at the bedrock and kept staying in the basin for a long time.

4) When the soft clayey soil was thickly deposited like Aso Caldera, the original natural period was long. In addition, the ground was disturbed during the earthquake and loses rigidity, so that the natural period became longer.

The results of this analysis suggest that the irregularity of the strata of Aso Caldera and the thickly deposited soft clayey soil may have caused localized and enormous seismic damage due to the 2016 Kumamoto earthquake. In the future, we will collect topographical and geological information of Aso Caldera and pursue more precise modelling (including 3D analysis). In addition, we will examine the effects of the time interval between main-shock and after-shock that occurred without a break, and the directivity of the input ground motion.

Many of the existing earthquake damage prediction methods, including liquefaction, are limited to vertical one-dimensional evaluations, and do not consider the excitation of surface waves or complicated interference with body waves. However, large cities such as Tokyo, Osaka, and Nagoya are almost exclusively located on sedimentary basins, and there are countless irregularly shaped grounds such as alluvial valleys with different rigidity contrasts in these sedimentary basins. Therefore, for precise ground damage prediction, it is important to understand the effects of stratum irregularities of various sizes, and to analyse seismic damage by multidimensional elasto-plastic seismic response analysis.

5. Acknowledgements

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6. References

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