Field investigation on a sinkhole developed in the loose volcanic ground

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ABSTRACT: Due to the typhoon on Sept.19, 2016, a large sinkhole occurred in a sweet-potato field, leading to a soil outflow of 1500 m^3 to the road nearby through a piping hole. The size of sinkhole was 31m long, 13m wide and 7m deep. The area is covered by the volcanic soil, called Shirasu, which generally has low density and high permeability. Surveys including dynamic cone penetration tests and surface wave surveys were conducted to identify the locations of subsurface cavities, water paths and loosened ground. Very loose Shirasu layer was identified above the impermeable clayey layer at the depth of about 12m. Water paths seemed to form within Shirasu layer and Shirasu was subjected to internal erosion. A relatively stiff layer was also found at a depth of 4m, below which the erosion seemed to be accelerated. Surface wave survey results indicated that water paths, the potential cause of sinkholes, were further extended. Judging from elongated shape of the sinkhole, two or three sinkholes simultaneously or successively occurred above the water paths.

Keywords: sinkhole; volcanic soil; internal erosion; surface wave survey; rainfall

1. Introduction

A large scale sinkhole appeared at Miyakonojo city, Miyazaki prefecture in Japan after the heavy rainfall due to typhoon No.16 on September 19, 2016. It occurred at the potato field beside the high-speed motorway. Fortunately there was no casualty, but the road was temporarily closed to traffic because the motorway of about 200 m was covered with soil flown out from the sinkhole.

This paper reports the outline of the field investigations conducted between December 2016 and May 2017 (Kominami, 2018), in order to understand the mechanism of formation of the sinkhole and search for underground water pathway which can be potential sinkholes.

2. Outline of the sinkhole

A photo of the sinkhole is shown in Fig. 1 and a cross section is schematically shown in Fig. 2. The sinkhole was found after typhoon No.16 had passed on September 19, 2016. The second largest intensity of rainfall, 88mm/h, in Miyazaki prefecture was recorded at around 2AM.

The sinkhole was ellipse shape, with about 31m long, 13m wide, and 7m deep. There was a gap of 2m high in the ground connecting between the bottom of sinkhole and the road running beside it, through which soil seemed to sprung out from the sinkhole. Estimated amount of soil outflow was about 1500m^3. Length of the gap in the ground was about 30m from the sinkhole to the road. The difference of altitude between the inlet and outlet of the soil traveling path was only 0.4m. Soil with water seemed to be pushed by a large pressure. Fig. 3 shows the outlet of the soil/water path observed from the road side.

The area was covered with loose and permeable volcanic soil, called Shirasu. According to the borehole survey near the sinkhole location, very loose Shirasu deposit of which SPT-N value was less than 3 appeared up to about 10m from the surface.

Figure 1. View of the sinkhole

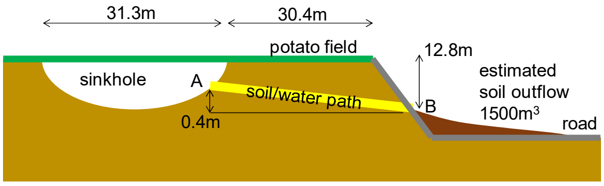

Figure 2. Cross section of the sinkhole

Figure 3. Outlet of the soil/water path, looking in the gap from B to A in Figure 2

3. Field investigation

3.1. Survey method

Field investigation was conducted with two stages. First, dynamic cone penetration tests and surface wave survey were carried out to search for subsurface cavities and loosened ground around the sinkhole. Tests were conducted in December 2016, March and April 2017.

Excavation and repair work of the sinkhole had started from May 2017. In that occasion, detailed observation of each soil layer, elastic wave survey and cone penetration tests were conducted.

3.2. Dynamic cone penetration test

Dynamic cone penetration tests, DCPT, were carried at 14 points in total, a to e and 1 to 9, as indicated in Fig. 4, in which values of DCPT resistance, N_d, at points a to e are also presented. DCPTs were conducted up to 12 m deep when it was possible. At point a, b, c and e, near the sinkhole, values of N_d are around 5 up to 5m deep. N_d values were 5 to 20 at greater depths. At point b, there was no DCPT resistance at 10 to 12 m deep. It seemed to correspond to the soil/water path of 2m high between the sinkhole and the road. At point c, at around 6m deep, the N_d values are fluctuated and no resistance was recorded twice, indicating voids in the ground. On the other hand, at point d, about 80m away from the sinkhole, N_d values increased at more than 5m deep, showing relatively stable ground condition.

Fig. 5 shows N_d values for points 1 to 9. In overall, when it is deeper than 6m, the deeper the ground is, the stiffer. Particularly a stiff thin layer was found at around 4m deep for points 1 to 9, as indicated in Fig. 5, which was not observed near the sinkhole, at points a to e.

3.3. Surface wave survey

Surface wave survey was conducted along 6 lines, A to F. Locations of the measurement, line lengths and the results are presented in Fig. 6.

In all measurement lines, S wave velocities at less than 6m deep are slower than 120m/s. On line B, where the

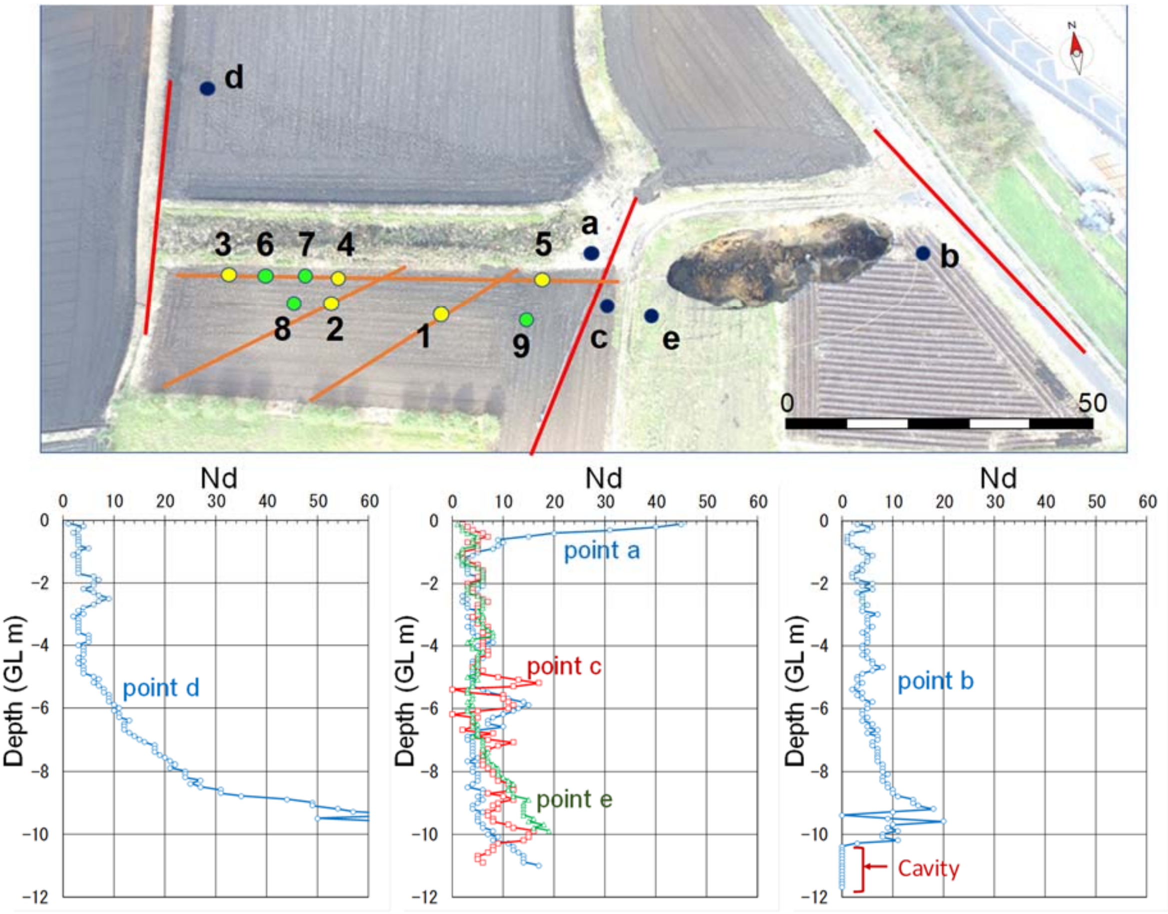

Figure 4. Measurement points for DCPT and penetration resistance, N_d, at points a to e

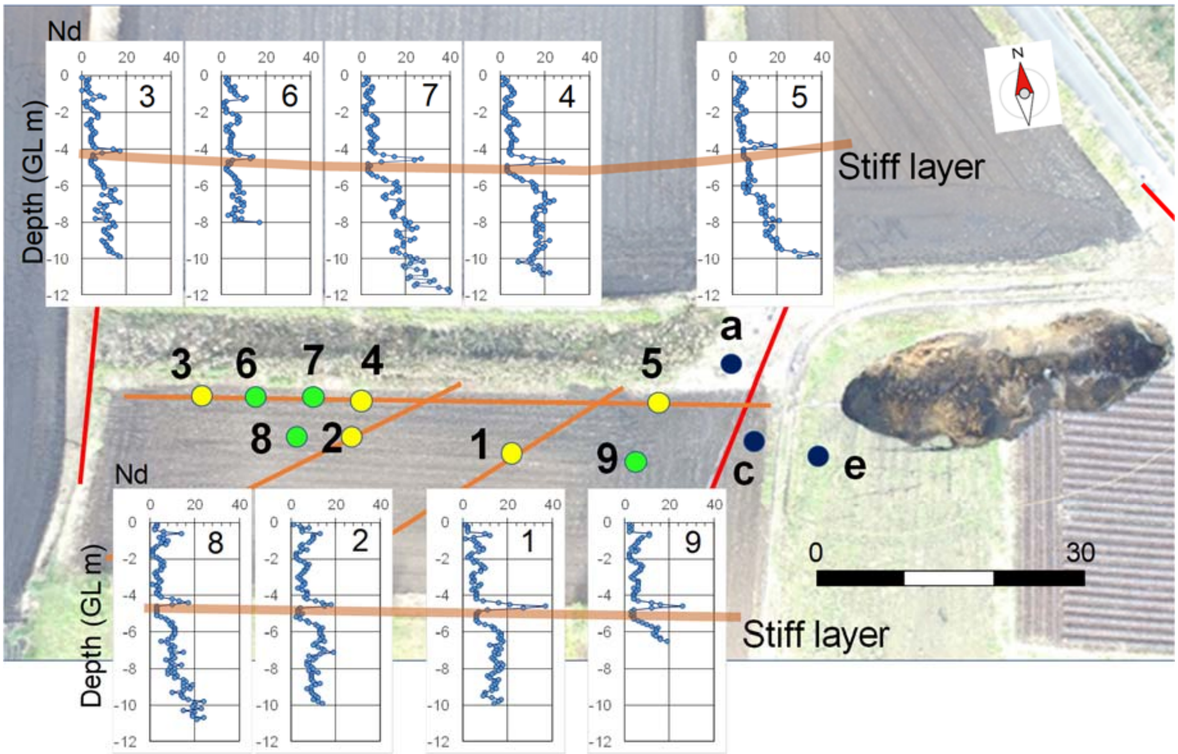

Figure 5. DCPT resistance at points 1 to 9

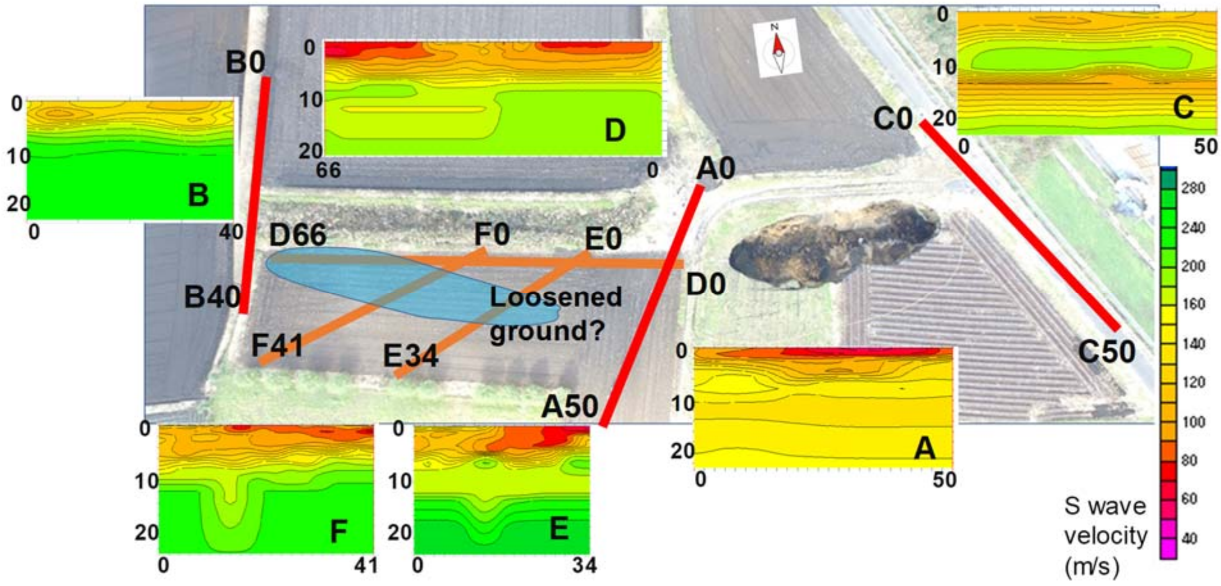

Figure 6. Surface wave survey

least influence of the sinkhole is expected, S wave velocity deeper than 6m is greater than 200m/s. On lines A and C, near the sinkhole, S wave velocities indicated the presence of loosened ground up to 10 to 15m. But in line C, the soil/water path in the ground could not be identified by the surface wave survey. In lines D, E and F, the results implied that there is a loosened area at around 10m deep.

3.4. Observation of soil layers

On the occasion of repair work of the sinkhole, the excavation was carried out around it. Fig. 7 shows photos before and after the excavation. Soil strata was exposed

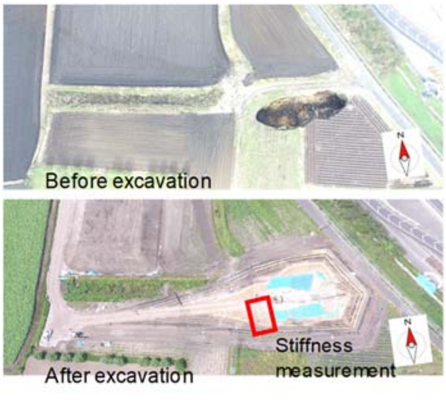

Figure 7. Around the sinkhole before and after excavation

and the evaluation of stiffness of each soil layer by the measurement of elastic wave velocity and cone penetration resistance, q_c, became possible, as shown in Fig. 8. Values of q_c were obtained using a portable cone penetrator. The location of the measurement is indicated in Fig. 7. Fig. 9 shows soil layers, cone penetration resistances and elastic wave velocities of each layer.

Elastic wave velocity measurement

Portable cone penetrator

Figure 8. Stiffness/strength measurement of soil layers

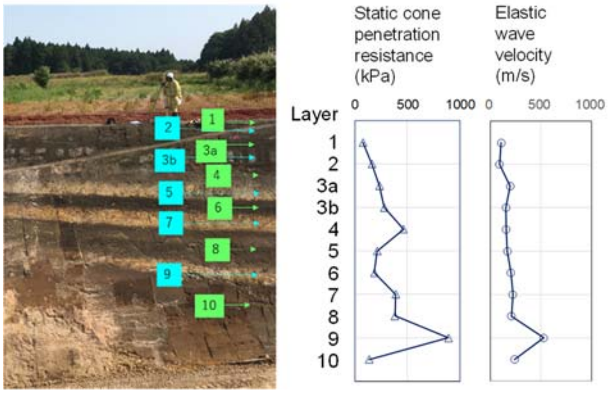

Figure 9. Cone penetration resistance and elastic wave velocities of soil layers

Values of elastic wave velocity and q_c showed similar trend. It was found that both wave velocity and q_c for layer 9 are notably larger, indicating stiffer and stronger soil layer. This thin stiff layer was also observed in the resistance of DCPT at point 1 to 9, as shown in Fig. 5, at around 4m deep from the surface. But it disappears at DCPT points a, c and e. It seems that the stiff layer (layer 9) gradually rising towards the sinkhole and disappear, as indicated in Fig. 10.

Figure 10. A stiff layer in the west of the sinkhole

Very loose and erodible volcanic sand layer 10 spreads below the stiff layer 9. When it was exposed, it was easily eroded by the rain, as shown in Fig. 11. At the location of the sinkhole, an impermeable clay layer lies below the loose volcanic sand.

Figure 11. Loose volcanic sand which was erodible easily by rain

3.5. *Physical and Mechanical properties of Shirasu*

Soil samples were taken from the sinkhole site from the depth of 11.8m. It seems to be layer 10, volcanic sand, Shirasu. Physical properties of the soil is shown in Table 1.

Table 1. Physical properties of Shirasu (Sato et al., 2018)

Soil particle density, ρ_s (g/cm^3)	2.43
Dry density, ρ_d (g/cm^3)	0.77 – 0.81
Water content, w (%)	41
Void ratio, e	2.01 – 2.16
Mean particle size, D_{50} (mm)	0.2
Fine content (%)	28
Plasticity	NP

The soil is categorised to be silty sand, containing 28% of non plastic fines. Soil particle density is low, reflecting the nature of volcanic porous particle. Dry density is also low, indicating very loose structure.

Three undisturbed samples were isotropically consolidated up to 50 kPa for S1, and 200 kPa for S2 and S2, respectively. Volumetric strains developed during isotorpic compression are shown in Fig. 12, in which volumetric strains of non-plastic silt compacted as loose as possible state, D4 and D5, was also shown. Volumetric strains of Shirasu was significantly larger than loose non-plastic silt.

S1 and S2 were sheared in the drained condition, while undrained compression was conducted for S3. Fig. 13 presents stress-strain relationships, volumetric strains, excessive pore water pressures, and effective stress paths. All three specimens showed strong contractancy. Samples seemed to have capacity for further contraction in the drained condition even at around 20% of axial strain. The shape of S2 specimen afer the test is presented in Fig. 14. The specimen kept cylindrical shape and no lateal buldging was observed. Fine content of S1 and S2 after the test was 31% and 38% respectively. Compared to the initial fine content of 28%, increase in fine content indicated the effect of particle crushing. In undrained triaxial compression, shearing continued after the stress point reached constant p' and constant q at an axial strain of 2%. It implies the soil has a potential for flow failure when it is subjected to rapid loading.

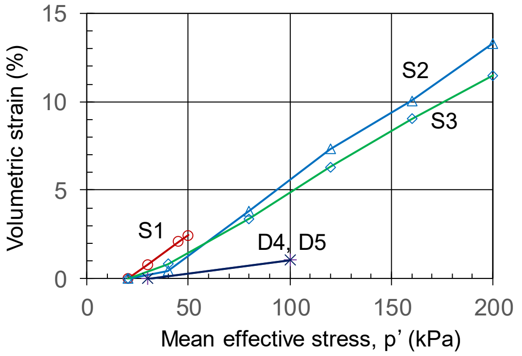

Figure 12. Volumetric strains during isotropic consolidation

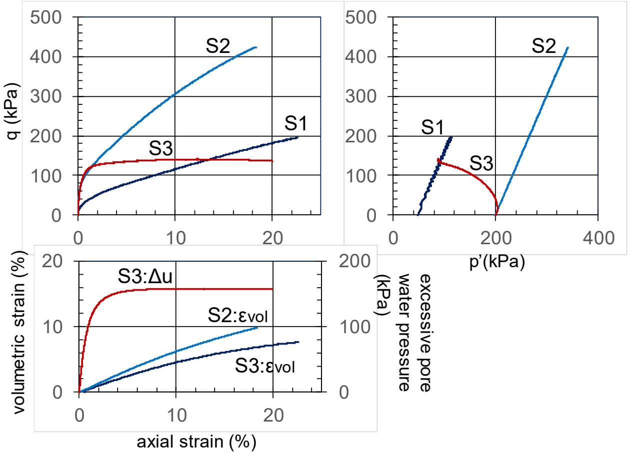

Figure 13. Drained and undrained triaxial compression for Shirasu

Figure 14. Shape of S2 specimen after CD test (confining pressure:200kPa, sheared up to axial strain of 20%)

4. Estimated mechanism of sinkhole formation

From field and laboratory investigations around the sinkhole, followings were observed.

- The area is covered with loose volcanic sand, Shirasu, of about 12m thick. It has large compressibility and is highly crushable. The volcanic sand layer deposits on an impermeable clay layer.
- Looser part was identified in the surface wave survey in the west side of the sinkhole at more than 10m deep.
- A thin stiff layer exists in the west side of the sinkhole at around 4m deep. Elevation of the stiff layer gradually rises in the east direction and it dissappears near the location of the sinkhole.

It is likely that a water path was formed on the boundary between clay and sand layer, due to contact erosion. Loose sand became even looser and weaker due to internal erosion. Voids or cavities may be developed. The water path seemed to be about 100m long at around 12m deep. The thin stiff layer at 4m deep may act as a kind of roof on the voids but it dissappears at the location of the sinkhole. Due to very heavy rain brought by typhoon, internal erosion was accelerated. The cover soil on the water path could not sustain and collapsed as schematically illustrated in Fig. 15. Judging from elongated shape of the sinkhole, two or three sinkholes simultaneously or successively occurred above the water paths.

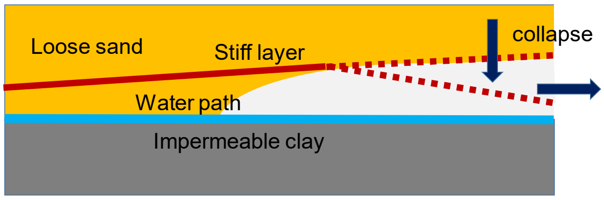

Figure 15. Estimated mechanism of sinkhole formation

5. Conclusions

Field investigation was carried out around the large sinkhole occurred in Sept.19, 2016 due to heavy rain caused by typhoon. Dynamic and static cone penetration tests, surface wave survey, elastic wave velocity measurements, soil sampling and some laboratory tests were conducted to obtain the structure of the ground and physical and mechanical properties of the key soil.

Results of investigation implied the presence of water path of about 100m lying at the depth of 12m, at the boundary of impermeable clay and loosely deposited volcanic sand. This possibly caused internal erosion and created voids and cavities in sand. A thin stiff layer at 4m deep may have helped to support the soil above cavities but when the cavity grew and expanded due to heavy rain, it could not sustain and finally collapsed. Considering very high compressibility and crushability of volcanic sand, it was probably liquefied at the moment of collapse. However, it is still surprising that such large amount of soil splashed out through a narrow gap of 30m distance.

Acknowledgement

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