AN EMPIRICAL METHOD FOR PREDICTING DAMAGE CAUSED BY AN EARTHQUAKE TO ARTIFICIAL HOUSING SITES

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SUMMARY

In this paper, the authors propose an empirical method for predicting damage caused by an earthquake to artificial housing sites. Investigating long term variation in N values in the damaged housing ground following the earthquake, the nature and extent of the damage to housing site under the circumstances of a similar earthquake in future can be predicted. The following steps can be followed to determine the risk of damage to housing sites; (1)Immediately after the earthquake, it is recommended that standard penetration test be carried out in the damaged housing ground. (2) In the approximately ten and twenty years following earthquake, the standard penetration test should be performed at the same location. (3)Consequently, if N values increase in the twenty years following the earthquake, no ground failure seems likely occur in the event of a similar earthquake. However, if no variation in N values be observed, some fissures or settlement appears to be likely to occur at these sites. In addition, if N values decrease in the twenty years following the earthquake, the housing ground will likely suffer severe damage.

INTRODUCTION

On June 12, 1978, an Earthquake off the coast of Miyagi Prefecture struck the suburbs of Sendai City, causing particularly severe damage to housing sites in Midorigaoka, Kitane-Ichinenbo, Aramaki-Genshinden and Tsurugaya in Sendai City, and Kotobukiyama in Shiroishi City, which were relatively new housing district. Immediately after the earthquake, prevention work such as the construction of retaining walls, steel pipe piling, and drainage wells were performed, and steel pipe pilings were installed in Midorigaoka and Kitane-Ichinenbo with the help of governments of Sendai City and Miyagi Prefecture. In addition, in Kotobukiyama district an earth moval project was performed. However, no repair work was performed in the Aramaki-Genshinden and Tsurugaya housing districts. In order to investigate long-term variation in soil properties such as the N values, physical properties, and mechanical properties in the ground below severely damaged houses, the authors performed borings, standard Japanese penetration tests and various other soil tests in 1978, 1985 to 1986, and 1996 to 1997. Soil surveys were performed at four locations in Midorigaoka, two locations in Aramaki-Genshinden, three locations in Tsurugaya and eight locations in Kotobukiyama.

MIDORIGAOKA

Fig.1(a) shows an aerial view of extremely damaged housing sites in Midorigaoka-1chome. Eleven houses in block A and seven houses in block B, indicating by hatching, were so severely damaged by the earthquake that their owners were obliged to move. Approximately twenty years ago, a steep valley at an angle of almost 15 degrees existed along the A-A' line of block A. Housing sites were constructed by filling in the slope of the valley with loam and gravel, fractured sandstone, mudstone and tuff to a depth of between 5m and 10m. This fill was not compacted. The cross-section along the A-A' line is shown in Fig.1(b). Loose sandstone and talus lies under the fill with N values varying from 0 to ten. The slope has moving both in the direction of A-A' and perpendicular to A-A'. In addition, in the six months following the earthquake, extreme variation was observed at

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a depth of 18.5m, suggesting the presence of a sliding plane within the sandstone bedrock. The southern portion of the area illustrated in Fig.1(a) is block B, another damaged housing area. Before the earthquake, seven houses marked by hatching occupied block B. However, all these houses were destroyed by the earthquake, and the inhabitants were forced to move elsewhere. Since the earthquake, a position of the embankment was removed and pipe piling were driven into the ground to stabilize this area. A cross-sectional view of the ground along B-B' line is shown in Fig.1(c). The B-B' line does not lie along the valley. When housing sites were constructed in this area, the slight slope was filled in using loam, gravel, sandstone and tuff. Standard penetration tests conducted on the hill at these sites revealed that the N value decreased between 0 and 5. The results suggest that housing sites near point B-3 sunk slightly in the half-year after the earthquake. In addition, the steel piling designed for and constructed in the damaged Midorigaoka area are shown in Fig.1(a) and 1(b). This area had been subjected to considerable ground movement. Static analyses were performed at two circular slip surfaces located at depth of 5.0m and 18.5m. Parameters used for analysis were based on a C-ϕ daigram employing the conventional stability analysis method with an induced strength of tan ϕ = 0.18 and C = 0, and a safety factor. Based on the results of these analysis, a buttress-type retaining wall with a steel pipe piling foundation was constructed at B.P-36, and steel pipe piling stabilizer were designed and constructed at B-1, SR-5 and B.P-13.

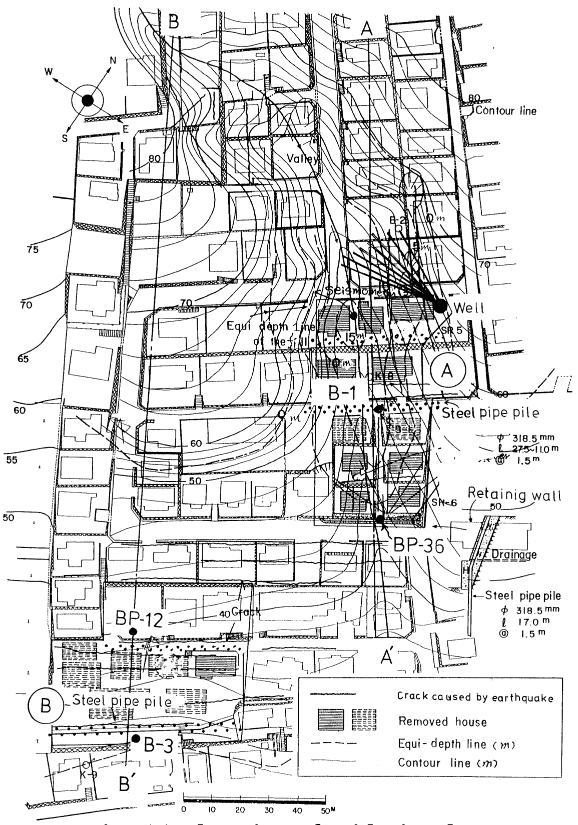


Fig.1(a) Plan view of Midorigaoka.

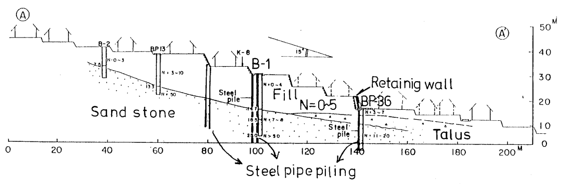


Fig.1(b) A-A' cross section.

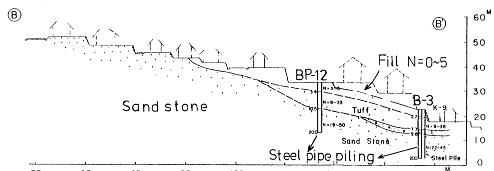


Fig.1(c) B-B' cross section.

Fig.1(b)&(c) Damaged housing sites

Steel pipe piling measuring 318.5mm in diameter were inserted into prebored holes to a depth of $1\frac{1}{3}$ times the thickness of the fill comprising the surface layer. An H beam was inserted into each pile, and the empty space remaining inside the pile was filled with concrete. The piles were sunk at intervals of 1.5 meters in two staggered lines. At B.P-36, a pre-existing concrete block wall was widened and a new concrete wall was built upon a steel pipe piling foundation. In addition, a reinforced concrete well measuring 5m in diameter was constructed to a depth of 20m at the upper portion in block A in order to collect ground water flowing along the valley using eight underlying horizontal pipes installed in the lower part of the well, resulted in a lower water table under the fill. After these repairs, the 18 houses in block A and B were forced to move and the ground was readjusted. Since then, no body has been allowed to live or enter these areas.

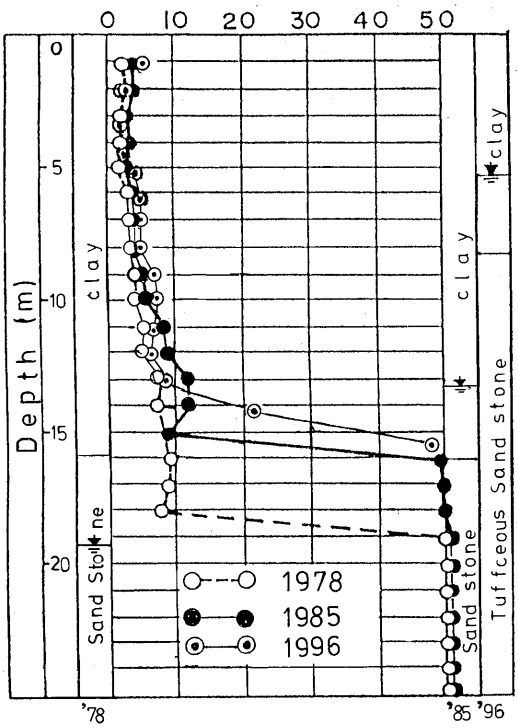


Fig.2(a) Variation in N values at B.P12 in Midorigaoka.

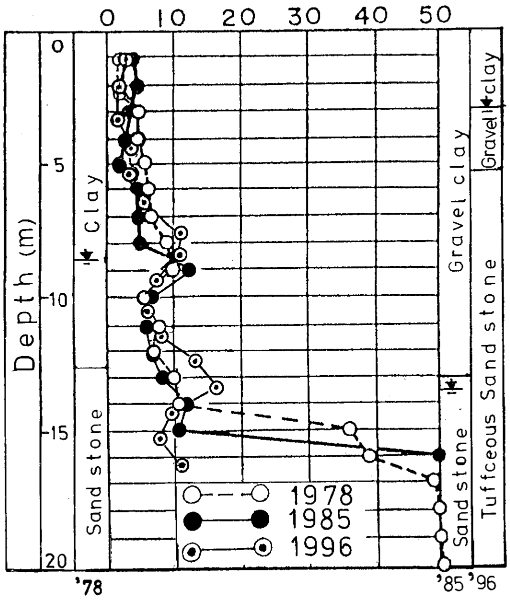


Fig.2(b) Variation in N values at B.P36 in Midorigaoka.

In order to investigate the effectiveness of repair works in the Midorigaoka housing sites, N values were measured in 1978, 1985 and 1997 using the standard Japanese penetration test. Based on the variation in N values over time after the earthquake, the stability of these housing sites is discussed as follows;

Boring location B-1

In Fig.2(a), the variation in N value at an interval of one meter is illustrated for 1978, 1985 and 1996. During the eighteen years following the earthquake, no variation in N values was observed at a depth of 0 to 13m. Immediately after the earthquake, a drainage well installed in the upper section of the block A in order to lower the water level, thereby increasing N values in the fill. Immediately after the installation of the drainage well, the ground water table was observed at a depth of approximately 19m. However, by 1996 the water table had risen to a depth of approximately 5m. Thus, we can say that the drainage did not show its desired effect, indicating that the housing sites near B-1 likely will suffer damage in the event of a earthquake.

Boring location B.P-36

In Fig.2(b), the variation in N values at an interval of one meter is illustrated for 1978, 1985 and 1996. In the eighteen years following the earthquake, no variation in N values was observed at a depth of 0 to 13m. Consequently it is clear that the housing sites near B.P-36 will likely suffer damage under the circumstances of a similar earthquake.

Boring location B.P-12

Fig.2(c) shows the distribution of N values obtained in 1978, 1985 and 1996. No variation was observed at a depth of 0 to 10m. Thus, the housing sites near B.P-12 are also likely to suffer damage under the circumstances of a similar earthquake in the future.

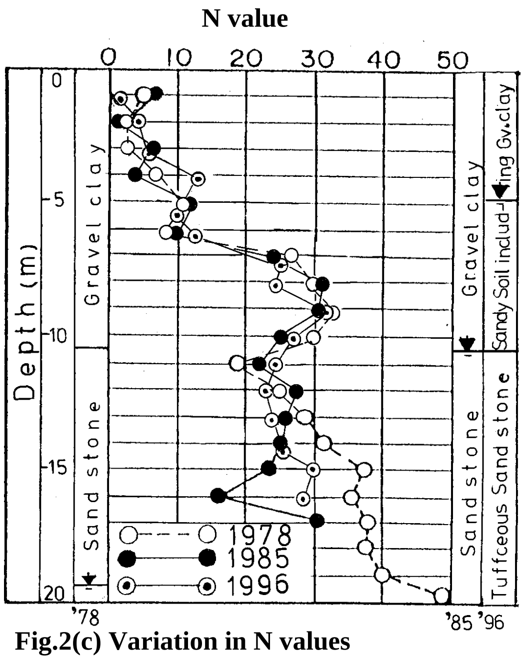


Fig.2(c) Variation in N values

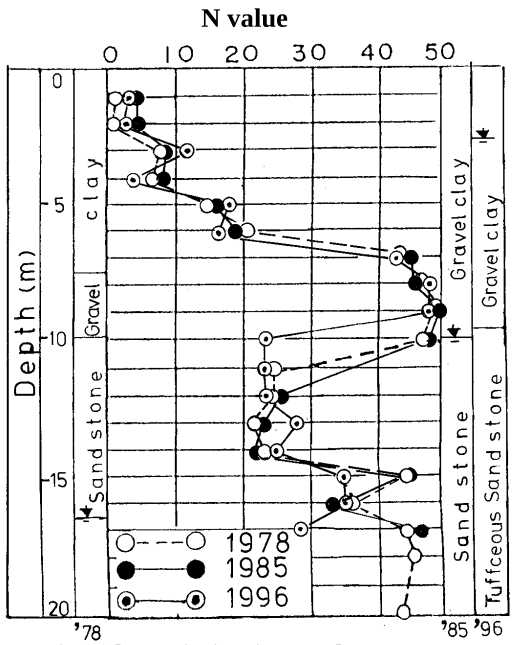


Fig.2(d) Variation in N values

Boring location B-3

Fig.2(d) shows the variation in the distribution of N values obtained in 1978, 1985 and 1996. No variation was observed at a depth of 0 to 10m, again indicating that the housing sites near B-3 are likely to suffer damage under the circumstances of a similar earthquake in the future. After the repair works were complete, 18 houses in blocks A and B were forced to move to other districts, and the ground was readjusted. Since then, no body has been allowed to live in these districts.

In order to investigate the effectiveness of repair works in the Midorigaoka housing sites, N values were measured in 1978, 1985 and 1997 using the standard Japanese penetration test. We believe that suitable action was taken at these sites by the Sendai City Government. Consequently, some fissures or settlements appear to be likely to occur at these sites, but the danger of slope failure has been greatly reduced due to the reconstruction of a retaining wall and the installation of the pipe piling.

ARAMAKI-GENSHINDEN

The Aramaki-Genshinden area is located in the northern section of Sendai City. Housing sites were constructed on a hillside, having an average inclination of 5 to 10 degrees from 20m to 80m above sea level from 1960 to 1962. The section underlying the rock bed was composed of loam, gravel, loose sandstone and tuff [Fig.3(b) and 3(c)]. Sites where houses received extreme damage were created using fill comprised of fractured rock. As shown in Fig.3(a), 8 houses were destroyed and 13 were partially damaged in this area. These houses were heavily damaged because they had been built on uncompacted fill. Conversely, houses built on the cut remained intact. Most of the houses built on the fill suffered severe damage due to ground fissures or collapse of masonry stone retaining walls. Housing sites were constructed by filling in the slope of the valley along Lines A-A' and B-B' to maximum depths of 10m and 8m, respectively. According to the standard penetration test, most of fill materials used registered N values between 1 and 10, as shown in Fig.3(b) and 3(c). In order to observe the long-term variation in ground movement, pipe strain meters were sunk into the ground at Points B-16, B-17 and B-17'. During the six months following the earthquake, no variation in strain was observed at these locations. Thus, no repair work was performed in the Aramaki-Genshinden housing area. As shown in Fig.3(a), locations B-17 and B-18 are in the right and left sections of Aramaki-Genshinden district, respectively. In Fig.4(a) and 4(b), variation in N values is indicated at an interval of one meter at locations B-17 and B-18 for 1978, 1986 and 1996. N values at a depth of 0 to 7m were lower in 1986 and 1996 than in 1978 at both locations B-17 and B-18. Thus, the housing ground softened during the eight years following the earthquake. Consequently, severe damage to houses seems likely to occur in the event of a similar earthquake because no preventive works were performed in Aramaki-Genshinden district.

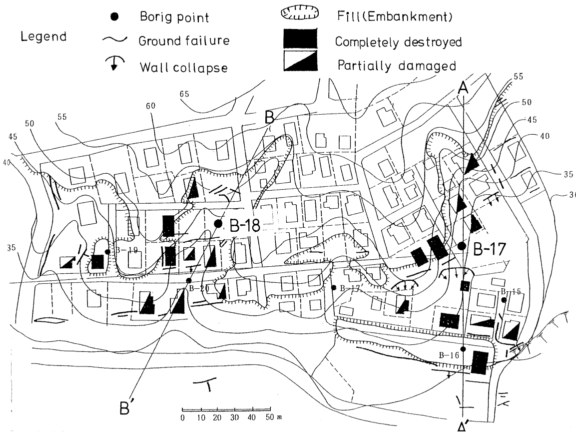


Fig.3(a) Plan view of Aramaki-Genshinden

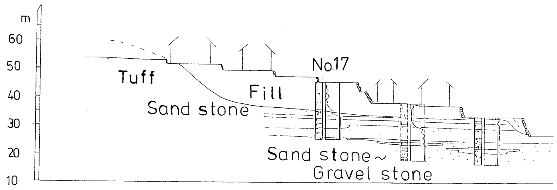


Fig.3(b) A-A' cross section

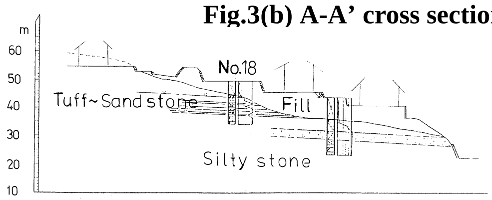


Fig.3(c) B-B' cross section

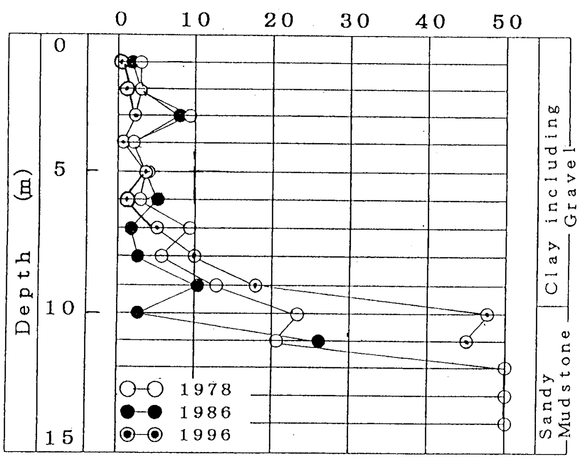


Fig.4(a) Variation in N values

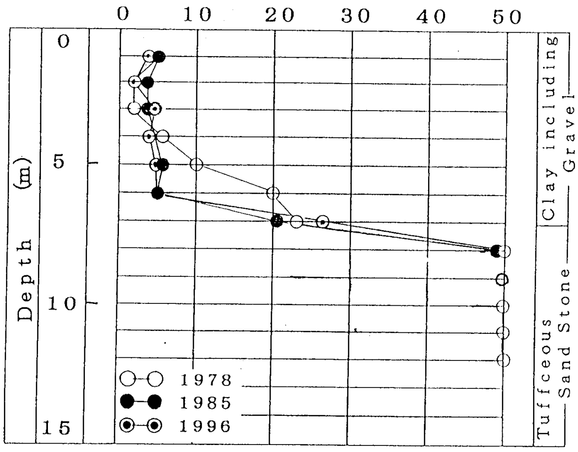


Fig.4(b) Variation in N values at No.18 in Aramaki-Genshinden.

TSURUGAYA

Tsurugaya housing district is located in northeastern Sendai City. Housing site was constructed on filling consisting of sandy soil on a hillside having an average inclination of 10 degrees and a maximum thickness of approximately 15m, as shown in Fig.5(b). The section underlying the bed-rock was composed of sandstone and tuff. Severe ground fissures were observed in fill consisting of fractured rock. According to a standard penetration test, most of the fill materials had N values ranging from 1 to 10. Fig.5(a) shows a plan view of sites containing severe ground fissures. Ground fissures occurred along the boundary between the cut and fill in the southern part of the road. However, in the northern part of the road fewer cracks were observed at top of the slope. The authors were concerned that slope failure might occur immediately after a future earthquake. In the southern section of the road, the fill that was piled around Apartments 9A-1, 9A-2, 5A-26 and 5A-27 subsided slightly during the earthquake. As a result, concrete slab pavement around the buildings settled and failed, and stairs were separated from one of the building. In the northern part of the road, gas pipes, water supply pipes, and drainage pipes were broken at several points due to ground fissures. A retaining wall supporting apartment 2B in block A was suspected to have been subjected to slight ground movement. Therefore, static analysis was performed at two circular slip surfaces. Parameters used for analysis were based on a C-φ diagram employing the conventional stability analysis method with an induced strength of tan φ = 0.28 and C = 0.95tf/m2, and a safety factor of 1.00 for one slip surface and 0.96 for the other. Based on this analysis, the following three measures were proposed to stabilize the retaining wall; (1) The construction of a new masonry block retaining wall with a reinforced concrete piling foundation. (2) The construction of reverse T-type retaining wall with a steel pipe pile foundation. (3) The construction of a concrete retaining wall with an earth anchor. However, none of these repair works were performed in block A. In block B, stability analysis were also performed on two circular slip surfaces that underlie the site's shallow and deep zones. Using a conventional analysis method, stability was determined to be 0.95 in the shallow zone and 0.69 in the deep zone. Based on these findings, lowering the ground water level in the shallow zone and the construction of a steel pipe piling stabilizer in the deep zone were recommended. However, these repair works were not performed. Boring locations B-2, B-3 and B-4 are shown in Fig.6(a), 6(b) and 6(c), respectively. As shown in Fig.6(a), 6(b) and 6(c), N values at B-2, B-3 and B-4 were lower in 1996 than 1978 and 1986. Thus, the housing ground near B-2, B-3 and B-4 softened in the eighteen years following the earthquake. Consequently, severe damage to buildings seems likely to occur in the event of a similar earthquake because no prevention work was performed in the Tsurugaya district.

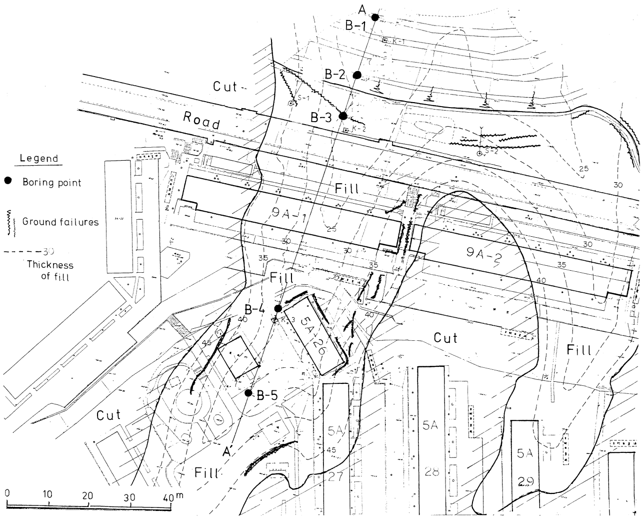


Fig.5(a) Plan view of Tsurugaya .

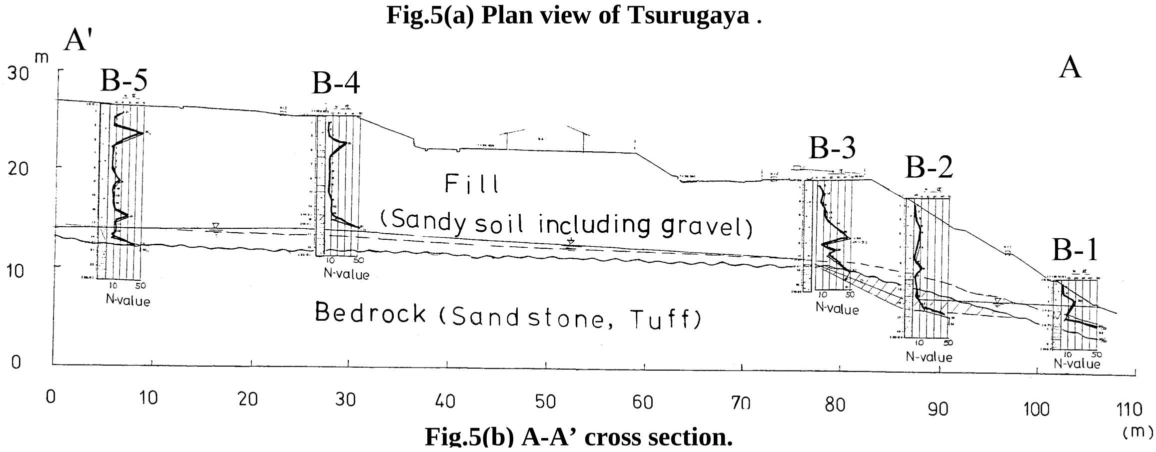


Fig.5(b) A-A' cross section.

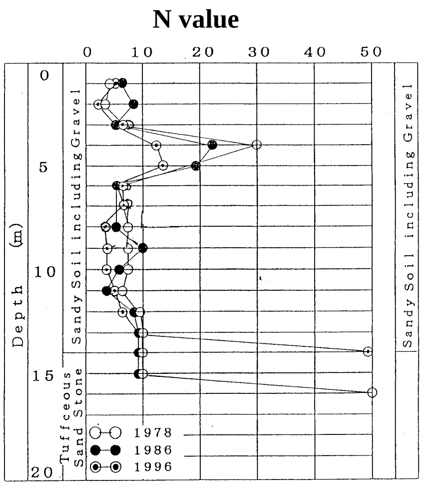


Fig.6(a) Variation in N values at B-2 in Tsurugaya.

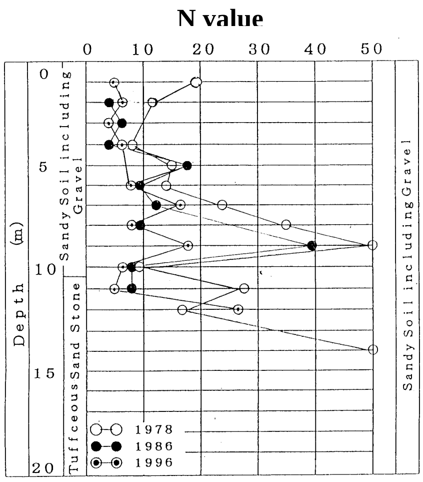


Fig.6(b) Variation in N values at B-3 in Tsurugaya.

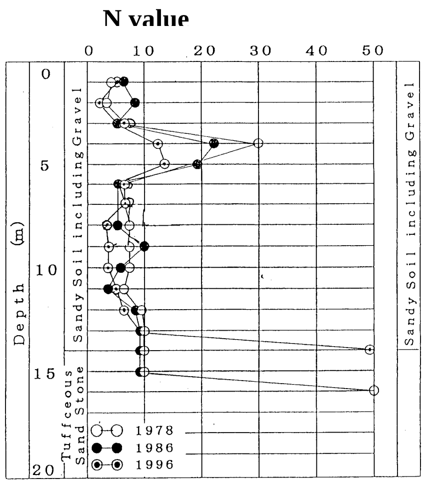


Fig.6(c) Variation in N values at B-4 in Tsurugaya.

KOTOBUKIYAMA

Fig.7(a) shows a map of Kotobukiyama that contains the housing sites that existed prior to development. Thin solid lines are counter lines following the natural ground before the housing sites were constructed. In 1970, there was a valley along the 8-8' line and a reservoir near the middle position of the 8-8' line. In 1972, ridges were cut and the valley filled with volcanic ash soils. As indicate by equidepth lines in Fig.7(a), the maximum depth of the fill was just 20m above the reservoir. Immediately after the earthquake, upper position of the slope above the reservoir started to collapse and shortly after there a large part of the fill behind the slope peak collapsed along the continuous line as illustrated in Fig.7(a). The collapsed mass of soil travelled a good distance aided by the water, coming from the water pipes. Because the housing sites were not yet ready for sale, only one man was killed by mud flow in the collapsed area. A cross section depicted the area along the 8-8' and 4-4' lines prior to development, after development, and following the earthquake are shown in Fig.7(b) and 7(c). As illustrated in these figures, estimates of the ground water table based on the boring work conducted in 1976 were relatively high for the land just above the reservoir. The ground-water appeared to flow down along the valley and the fill was almost saturated just before the earthquake. Immediately after the earthquake, spring water was found on newly shifted surface of the fill, and residual soils flowing downward. To best determine the causes of slope failure, many kinds of soil exploration, such as boring, sampling and sounding were conducted two weeks after the earthquake. N values in the fill, as determined by standard penetration tests in Fig.7(b) and 7(c), fell in the 5 to 10 range. It can be concluded from these results that the collapsed housing sites must have been unstable just before the earthquake.

Significant unevenness in unit weight and compression suggest that the earthquake should have been more solidly constructed. Immediately after the earthquake, the authors investigated the causes of ground failure and, as a result, proposed an earth removal project. The ground was readjusted at a 15 degree slope. In addition, a reinforced concrete well measuring 5m in diameter was constructed to a depth of 20m. Since completion of this construction, no body has been allowed to live in this areas.

Boring locations No.24 and 26

Fig.8(a) and 8(b) shows the distribution of N values obtained at boring No.24 and No.26 in 1978,1986 and 1997. N values at a depth of 0m to 7m increased overtime respectively. A reinforced concrete well resulted in a lower water level. Thus, no ground failures seems likely to occur in the event of a similar earthquake.

Boring locations No.21, 25 and 28

Boring locations No.21, 25 and 28 is shown in Fig.7(a). Figs.8(c), 8(d) and 8(e) show the distribution of N values obtained at boring locations No.21, 25 and 28 increased over time respectively. N values at a depth 0m to approximately 12m decreased over time at each boring locations. These penetration tests were performed in the ground after the earth removal and readjustment at a 5 degree slope. In Figs. 8(c), 8(d) and 8(e), averaged N values fell in approximately 5 in 1997. This N value is similar to averaged N value in the Midorigaoka housing sites immediately after the earthquake, in which severe damage to houses occurred. Thus, ground failure seems likely to occur in the event of a similar earthquake. However, the danger of slope failure has been reduced due to readjustment at a 5 degree slope.

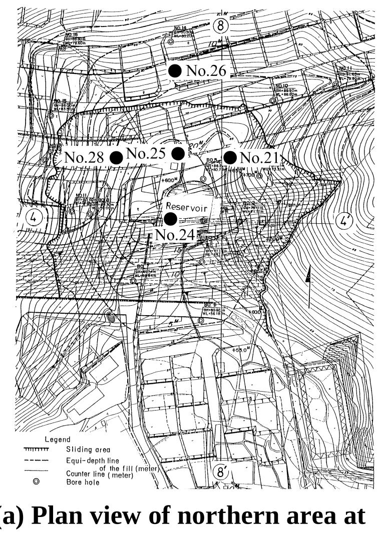
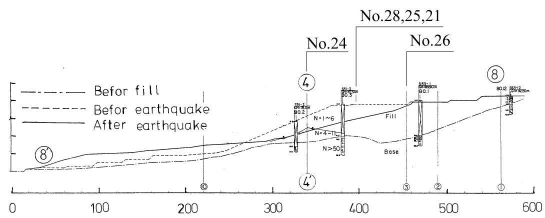
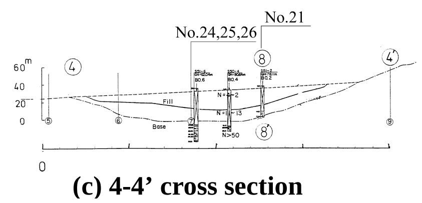


Fig.7(a) Plan view of northern area at Kotobukiyama.

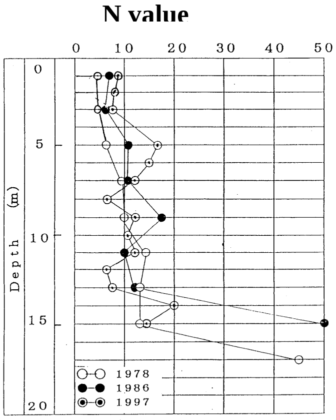


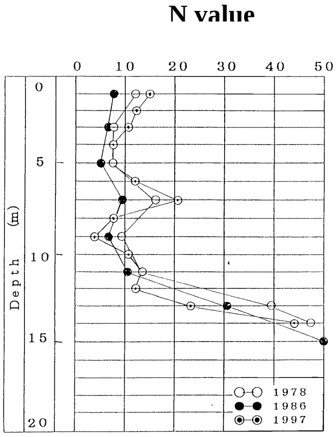
(b) 8-8’ cross section



(c) 4-4’ cross section

ig.7(b)and(c) Damaged to Kotobukiyama areas housing site.





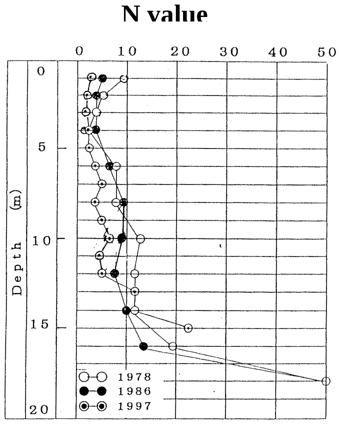
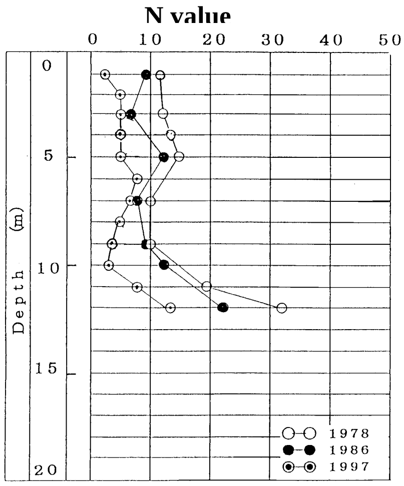


Fig.8(a) Variation in N Value Over Time at No25 in the Kotobukiyama

Fig.8(b) Variation in N Value Over Time at No26 in the Kotobukiyama

Fig.8(c) Variation in N Value Over Time at No21 in the Kotobukiyama



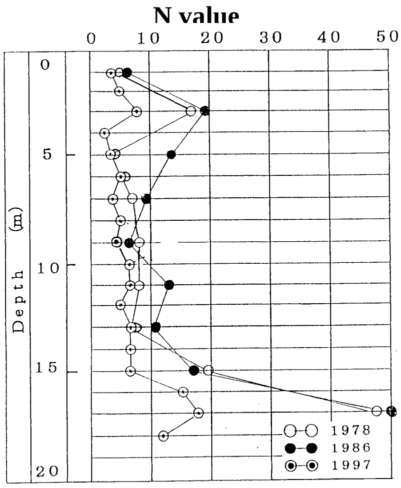


Fig.8(d) Variation in N values at No24 in Kotobukiyama.

Fig.8(e) Variation in N values at No28 in Kotobukiyama.