17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Evaluation of seismic behavior of upstream tailings storage facility applied liquefaction mitigation by wide-pitch lattice-pattern-walls type soil solidification

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Abstract

In this study, the authors examined three years of seismic records from large-scale slopes at an upstream-type tailings storage facility with wide-pitch lattice-pattern-walls type soil solidification applied as a liquefaction countermeasure. The findings are summarized below. 1) In line with the transfer function of ground response acceleration in the slope, ground improvement increased solidity by a factor of 2.9 to 5.5 as compared to the initial soil. The effectiveness of the countermeasure was maintained for 1.5 to 4.5 years after completion with no change in the transfer function. 2) The model for prediction of underground acceleration at the local site (based on the correlation between observation records of underground acceleration at the site and data from a nearby observation point as recorded by the National Research Institute) accurately reproduced actual reference records of observation conducted at the site. Accordingly, if such a prediction model can be formulated from seismic observation records covering a certain period, basement acceleration at the local site can be accurately estimated from nearby observation records if observation of ground motion at the local site is interrupted. 3) For real-time earthquake damage evaluation, facility safety can be judged immediately after tremors by comparing input ground motion estimated using the prediction model with the design value. 4) With the ability to evaluate tolerable seismic ground motion at the site via repeated simulation using an analytical model that represents observed seismic response, re-evaluation seismic ground motion values can be replaced with design values to improve the accuracy of safety evaluation. Such evaluation can be performed using large-scale three-dimensional elasto-plastic FEM seismic response analysis with high-performance computing technology.

Keywords: Tailings Storage Facility; Liquefaction Mitigation; Soil Mixing; Seismic Observation; Real-time earthquake damage assessment

1. Introduction

Incidents involving failure of and leakage from tailings storage areas [1, 2] have created an international need to ensure the stability of such facilities [3], whether still currently operational or closed. Loosely deposited tailings tend to readily liquefy in earthquakes, creating a risk of facility slope collapse. Consequently, seismic countermeasures are currently implemented in Japan for upstream raised-embankment-type facilities with deposits of 50,000 m^3 or more. In previous study [4], the authors applied cement-mixing lattice-pattern-walls type soil solidification with a wide-pitch and a low replacement ratio to a large slope at a tailings storage facility as a liquefaction countermeasure.

Performance design was implemented after centrifugal model tests to evaluate the seismic behavior of the improved ground, and laboratory mixing tests were performed on the acidic tailings to support the application of a mixture with high cement content, and seismic observation of the slope was continued. Recent quality checking work [5] based on evaluation of the overall shear wave velocity of composite ground improved by grid solidification has been conducted with a microtremor array and subsequent comparison with design values, but such evaluation is qualitative. As detailed in previous research by the authors [4], seismic observation enables quantitative evaluation of behavior in improved ground.

In this study, the authors analyzed three years of seismic observation data from a tailings storage facility with focus on long-term performance evaluation. A method for evaluation of local-input seismic ground motion based on public seismic observation records from a nearby site was then examined to support analysis of seismic behavior in the event of any interruption in base-input wave seismic observation, and potential utilization of monitoring data was discussed.

2. Seismic behavior and long-term performance evaluation

2.1 Overview of the tailings storage facility, seismic observation and seismic behavior

Table 1 and Fig. 1 outline the upstream raised-embankment tailings storage facility targeted for seismic observation. Disposal at the site was completed in 1977, and a 150-m slope there was improved between 2014 on 2015 via wide-pitch lattice-pattern-walls type soil solidification (average replacement ratio: 20%) as a measure to prevent spillage caused by liquefaction in a strong (Level 2) earthquake. Seismometers were deployed in the base and on the surface of the improved slope and on the flat ground surface of an unimproved upstream pond. Seismic observation was started in March 2017, approximately a year after the completion of construction. In previous work [4], the authors evaluated the average transfer function of the horizontal component of acceleration on the ground surface and in the ground using 13 seismic records from observation conducted between March 2017 and August 2017 (Fig. 2). The results showed that the primary dominant frequency was approximately 2 Hz in unimproved ground before countermeasure application and approximately 5 Hz in improved ground after countermeasure application. With conversion to a solidity value, improvement produced an increase of 2.9 to 5.5 times as compared to the initial ground, which was consistent with the improvement effect expected in design for the rigidity of the ground as a whole [4].

Seismic observation has been ongoing since March 2017. Among data from 387 records judged to correspond to earthquake profiles presented by the Japan Meteorological Agency from March 2017 to July 2019, 83 records with high signal-to-noise ratios were identified for evaluation of the transfer function. Fig. 3 shows a distribution map of target-record epicenters, and Fig. 4 shows the transfer function of the horizontal

Table 1 Overview of the tailings storage facility [4]

Location	Oguchi, Isa, Kagoshima, Japan; No.2 facility
Tailings disposal period	1937- 1977, including a long-term intermission in the middle of the term
Disposal method	Upstream raised-embankment type
Total area	350,000 m^2
Volume of deposited tailings	270,000 m^3
Slope potion	150 m (length), 20 % (average gradient)
Liquefaction countermeasure	Improvement was carried out between April 2014 and March 2015 using the cement deep mixing (CDM) method (20,296 m^3) for the upstream wall and the power blender method (32,800 m^3) for the wide-pitch lattice-pattern-walls type soil solidification part (the average replacement ratio: 20%, the width of the walls: 1.0 m, the pitch of the walls: 10 m).
Seismic observation	Seismic observation has been ongoing since March 2017.

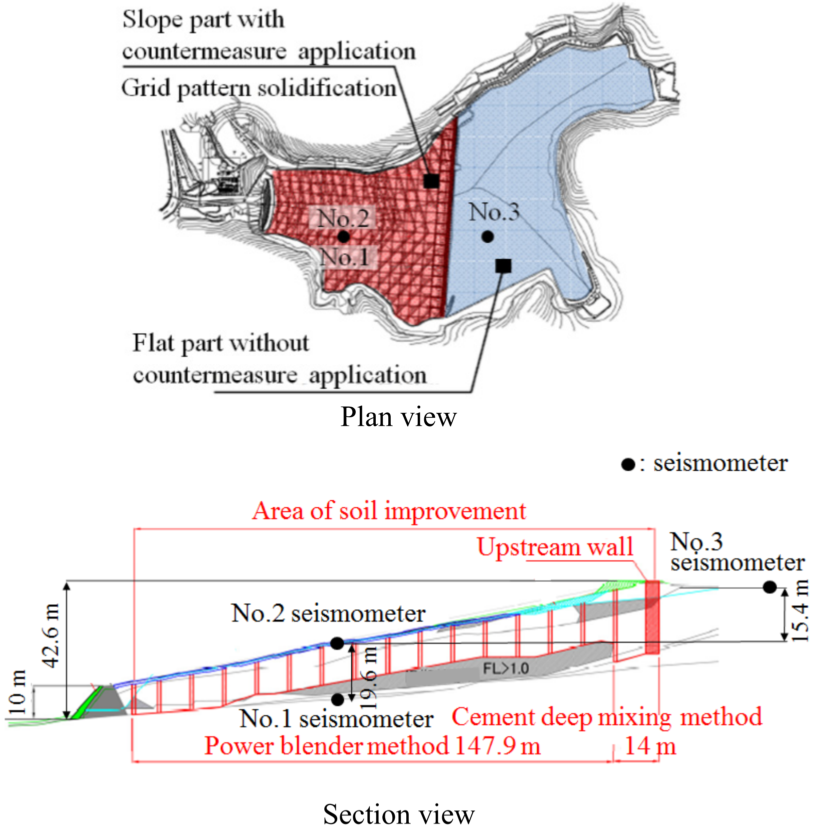


Fig.1 The tailing storage facility: Implementation of lattice-pattern-walls type soil solidification for the whole slope[4]

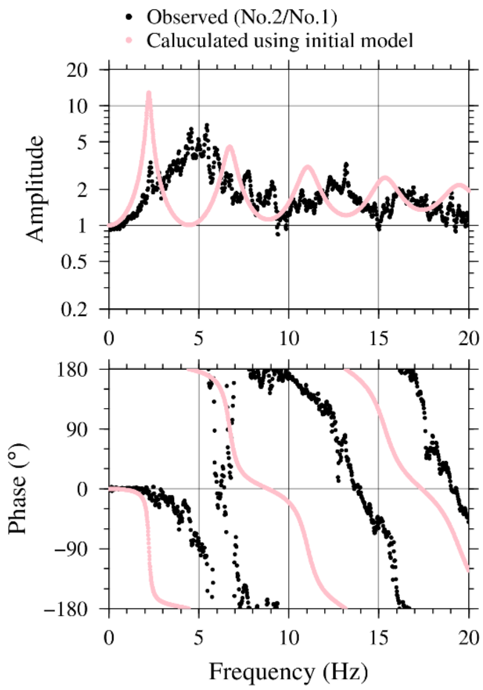
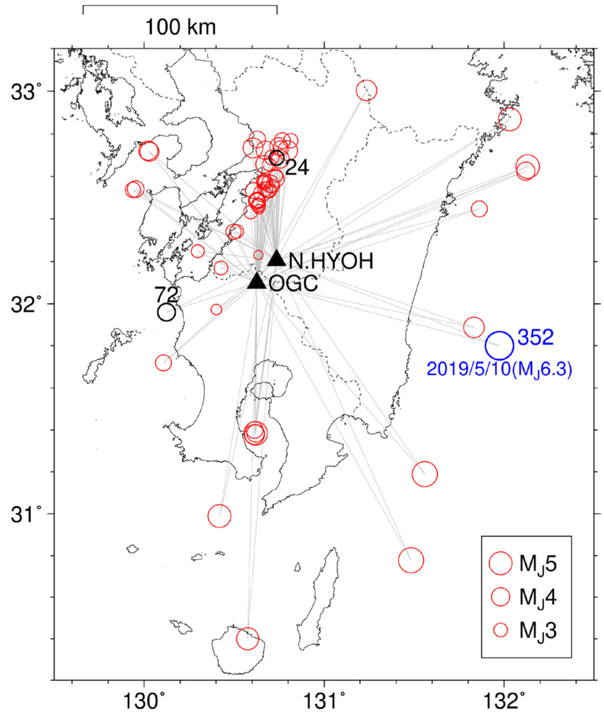


Fig. 2 Comparison of the transfer function (No.2/No.1) of the observed records with the calculated one using the initial 1D ground model without countermeasure [4]

component of the ground surface and underground compared with the average transfer function evaluated from all 83 records and the average transfer function from 13 records used in previous research. These 83 records exhibit fine smoothed peaks and valleys due to the effect of the ensemble average. There is no significant difference in overall amplitude characteristics (primary natural frequency: approximately 5 Hz) or phase characteristics, indicating that average transfer characteristics can be sufficiently determined via examination using only the 13 records obtained during a short period.



Notes:

No.24 earthquake (May 30, 2017, Mj3.3)

No.72 earthquake (June 3, 2018, Mj3.9)

No.352 earthquake (May 10, 2019, Mj6.3) caused the maximum acceleration response at the Oguchi site since the start of the seismic observation March 2017.

Fig. 3 Epicenter locations

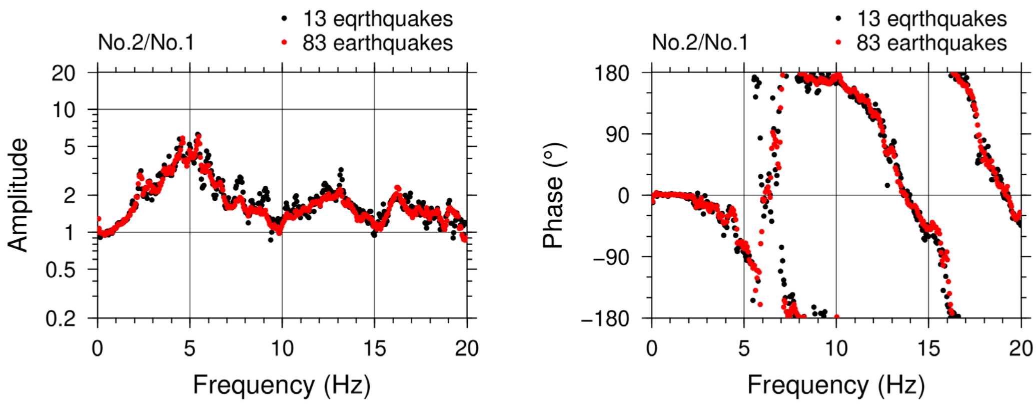


Fig. 4 Transfer function comparison of 83 records in this research with 13 records in previous study

2.2 Long-term performance evaluation and related discussion

The observation period was divided into three parts with similar data volumes, and the average transfer functions based on evaluation of records from each period were compared. The results shown in Fig. 5 indicate no obvious difference in transfer functions for the observation period. In Fig. 6, the maximum acceleration measured underground is divided into 10 Gal or more, 1 Gal to 10 Gal, and less than 1 Gal, and the average transfer characteristics are compared. Only one record (No. 352) shows 10 Gal or more. The transfer function evaluated from each record was smoothed using a Parzen window with a bandwidth of 0.2 Hz. For the transfer function of 10 Gal and above, the phase appears to be slightly shifted toward the lower-frequency side as compared to the other functions, but no clear difference in either phase or amplitude is observed. In each category, the primary natural frequency is approximately 5 Hz. No clear nonlinear response characteristic is associated with the amplitude level of ground response acceleration, and no temporal change at 3 or 4 years after construction was observed compared to results from 1 or 2 years after construction.

Natural frequency corresponds to the improved ground's equivalent rigidity, which is a major influencing factor in overall improved ground response. As the observation records detailed above indicate no temporal change in response characteristics, no degradation affecting overall response within the range of the observation period is considered to have occurred. Ongoing analysis and consideration in this regard are expected to support evaluation of long-term performance in improved ground. However, in consideration of the difficulty of long-term monitoring using seismometers (e.g., in relation to cost-effectiveness regarding the service life of instrumentation and maintenance expenses), the ability to verify consistency between microtremor array records and strong-motion observation records would increase the utility of microtremor arrays as a substitute for long-term performance evaluation. Meanwhile, enhanced observation for results with high density/accuracy and/or monitoring of strain in improved ground using strain sensors (e.g., optical fiber types) would support evaluation to determine the long-term performance of local portions (such as locations where responses are concentrated), which cannot be evaluated exclusively from overall response behavior.

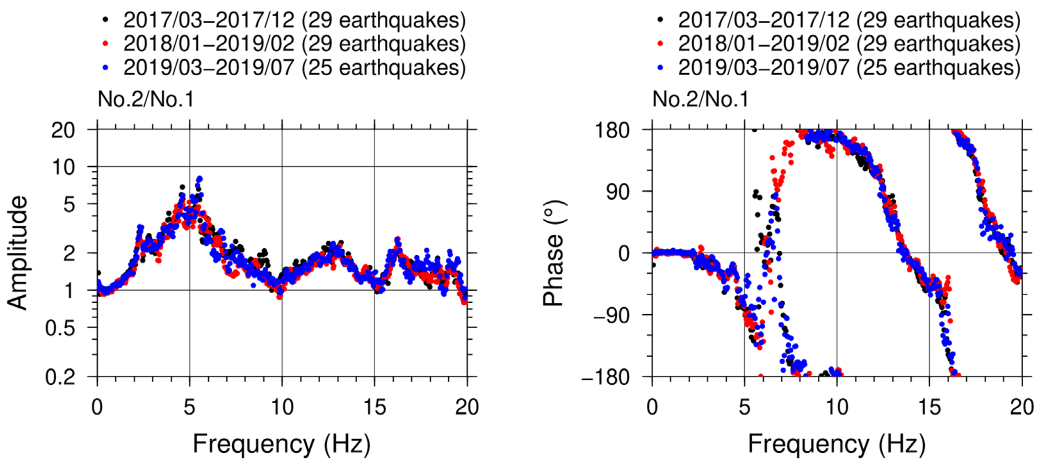


Fig. 5 Transfer functions for the records divided by three parts with the periods

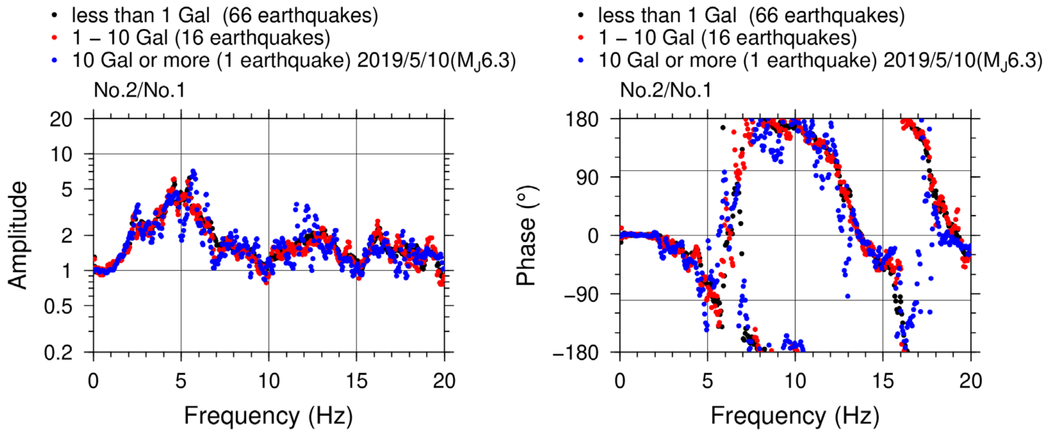


Fig. 6 Transfer functions for the records divided by three parts with the maximum accelerations

3. Stability monitoring and real-time damage assessment

3.1 Evaluation of local-site input ground motion

3.1.1 Outline

Seismic ground motion at Japan's Oguchi tailings storage facility (OGC) was compared with results from the nearby Hitoyoshi observation point (N.HYOH) to determine the capacity for ground motion estimation at Oguchi with correction for related characteristics. Acceleration waveforms converted from the high-resolution seismic observation network (Hi-net) based on records from an underground observation point at KiK-net Hitoyoshi (GL-123 m) located approximately 16 km from Oguchi were used as reference data. Among regular observations conducted at OGC and N.HYOH, 59 records collected from March 2017 to the end of July 2018 with a relatively small influence from noise and a distance from the epicenter of less than 200 km were selected for consideration.

3.1.2 Methodology

The acceleration Fourier amplitude of earthquake-associated OGC records is denoted by $A1(\omega)$, and that of N.HYOH records is denoted by $A2(\omega)$, with assumption based on approximation of the far S wavefield as follows:

$$A1(\omega) = S(\omega) / X1 \times \exp(-\omega X1 / (2Q(\omega)\beta)) \times G1(\omega) \ , \tag{1}$$

$$A2(\omega) = S(\omega) / X2 \times \exp(-\omega X2 / (2Q(\omega)\beta)) \times G2(\omega) \ . \tag{2}$$

Here, $S(\omega)$ is the amplitude representing ground motion radiating from the epicenter. X1 and X2 represent the epicenter distances for OGC and N.HYOH, respectively. $Q(\omega)$ and β represent the Q value and S wave velocity of the propagation path. $G1(\omega)$ and $G2(\omega)$ represent the respective ground amplification characteristics of OGC and N.HYOH.

Assuming that $S(\omega)$, $Q(\omega)$ and β are similar for the two records, the logarithm of the ratio for both gives:

$$\ln(A1(\omega) / A2(\omega)) - \ln(X2 / X1) = a + b(X1 - X2) \ , \tag{3}$$

$$a = \ln(G1(\omega) / G2(\omega)) \ , \tag{4}$$

$$b = \omega / (2Q(\omega)\beta) \ . \tag{5}$$

With the assumption of the model, the relative ground amplification characteristics $G1(\omega) / G2(\omega)$ and $Q(\omega)$ are derived from the regression coefficients a and b obtained via regression analysis using all records for each frequency. Using the modeled Q value and the relative ground amplification characteristics, the amplitude Fourier spectrum $F2(\omega)$ for all records from N.HYOH is subjected to amplitude correction as below for estimation of the OGC acceleration Fourier amplitude $F1(\omega)$. The estimated acceleration waveform of OGC can then be obtained via Fourier inverse transform.

$$F1(\omega) = X2 / X1 \times \exp(-\omega(X1 - X2) / (2Q(\omega)\beta)) \times G1(\omega) / G2(\omega) \times F2(\omega) \quad (6)$$

3.1.3 Evaluation results

As there was no significant difference in the analysis results for the two horizontal components in terms of relative ground amplification characteristics, only the results for the EW component in the direction of the slope of the tailings storage facility are given here. Fig. 7 shows the evaluation results for relative ground amplification characteristics $G1(\omega)/G2(\omega)$ obtained from the regression coefficient a. These characteristics fluctuate greatly with frequency, and the relative ground amplification factor exceeds 1 in bands around 1 to 4 Hz and around 7 to 20 Hz. The OGC values are slightly more amplified than those of N.HYOH. Meanwhile, at around 5 Hz in the primary natural frequency of the improved surface ground, ground amplification was smaller in OGC. Fig. 8 shows $Q(\omega)$ obtained from the regression coefficient b with the assumption of $\beta = 3.5$ km/s. $Q(\omega)$ approximated by $Q(\omega) = 50f^{0.6}$. This result was similar to that obtained by Izutani [6] based on the double spectrum ratio method in southern Kyushu. After the Q value was modeled and constrained to $Q(\omega) = 50f^{0.6}$, the relative ground amplification characteristics were re-evaluated and exhibited no significant change, as shown in Fig. 7. Based on the above, these values were used in modeling.

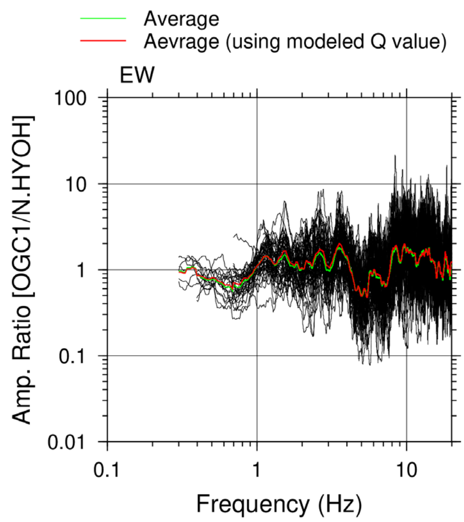


Fig.7 Relative ground amplification characteristics

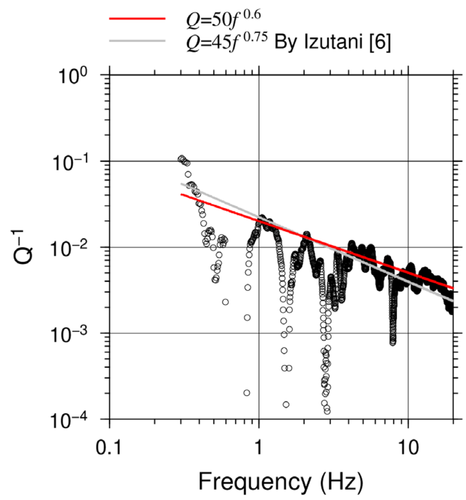
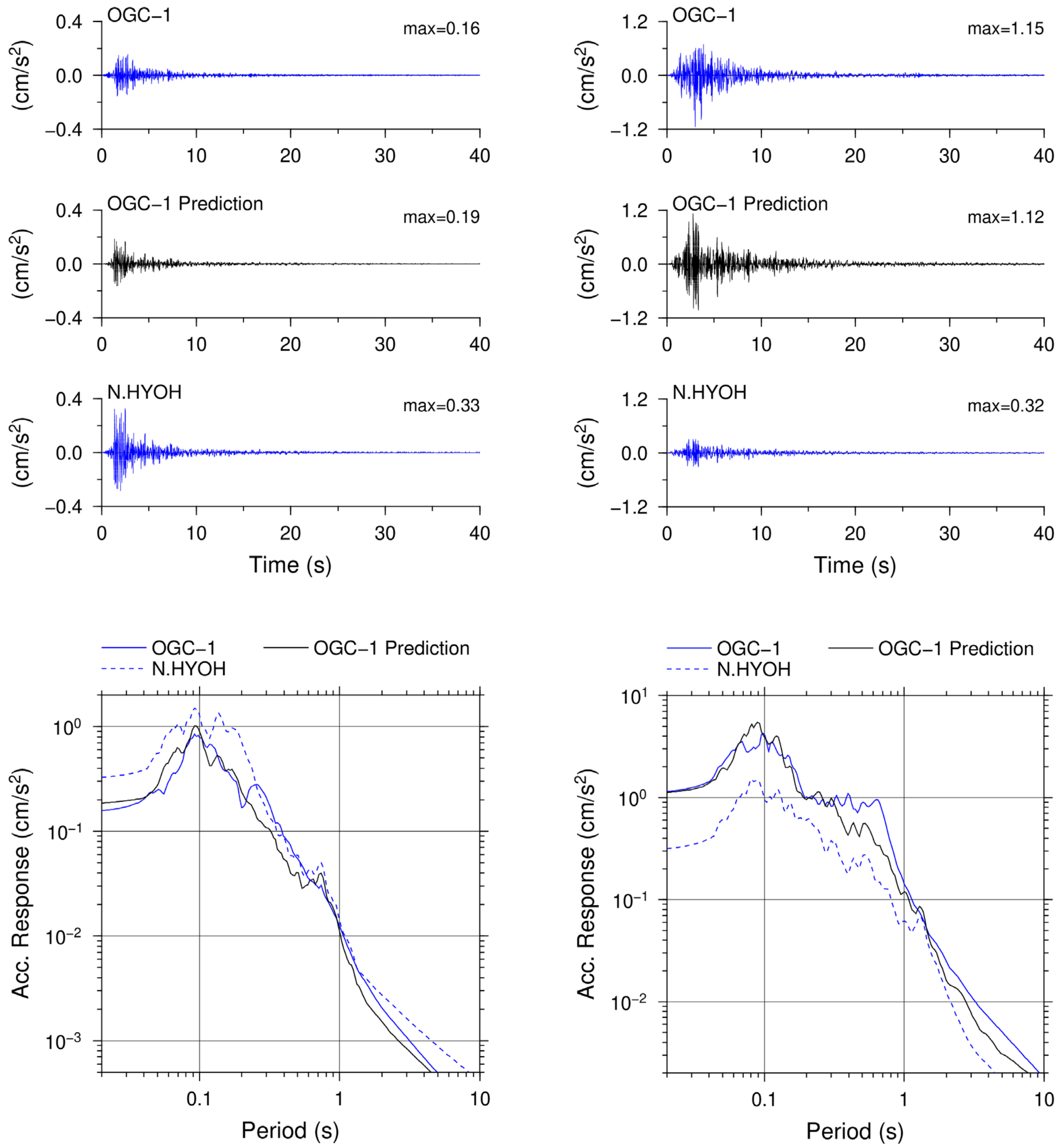


Fig. 8 Evaluation of Q value

Fig. 9 compares the estimated and observed acceleration waveforms for OGC, and highlights the pseudo acceleration response spectrum (h = 5%) as an index of related reproducibility. Records for N.HYOH are also shown in the figure. It can be seen that estimation results close to those of the OGC records were obtained for all waveforms, maximum accelerations and response spectra. Fig. 10 shows the response spectrum ratio between observation records and estimation results based on amplitude correction. The average value is close to 1, and correction can be considered to have reproduced average characteristics well. From the above, if such an estimation formula is obtained from seismic observation records for a certain period, the base site acceleration of the local site can be accurately estimated from nearby public observation records immediately after an earthquake even if observation at the local site is interrupted.



Accelerations in the No.24 earthquake　　Accelerations in the No.72 earthquake

Fig. 9 Comparison of observed and estimated acceleration (EW component) at the Oguchi site
Upper: waveforms, Lower: Pseudo acceleration response spectrum (h = 5%)

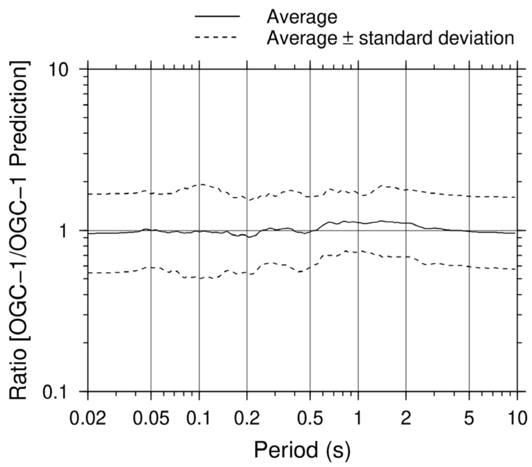


Fig.10 Response spectrum ratio between observed records and estimated results based on amplitude correction at the Oguchi site

3.2 Considerations for real-time damage assessment

Fig. 11 shows the waveform of an acceleration record from the Oguchi site during the 2016 Kumamoto Earthquake (April 16, Mj7.3) as estimated from Hitoyoshi KiK-Net observation records. Fig. 12 shows the results of comparing the acceleration response spectrum of the estimated wave with that of anticipated seismic ground motion in the design for earthquake countermeasures at the site. As the Oguchi record is much smaller than that of the design wave, the facility can be considered safe. When the Hitoyoshi KiK-Net observation records were released, seismic motion at the Oguchi site could be estimated in consideration of the characteristics of the local site, and the safety of the facility could be evaluated by comparing the estimated wave with the design wave.

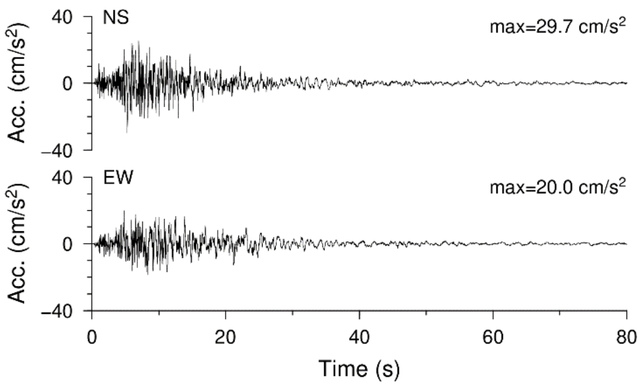


Fig. 11 Waveforms of an acceleration record from the Oguchi site during the 2016 Kumamoto Earthquake (April 16, Mj7.3) as estimated from Hitoyoshi KiK-Net observation records.

The benefits of seismic observation can also be considered in relation to validity assessment for facility design assumptions. As various assumptions are made in design, facilities do not always respond as expected. To address this issue, FE seismic response with various types of ground motion can be conducted in design checks using an analytical model that can reproduce actual observed seismic response to re-evaluate the maximum tolerable ground motion. Replacing the re-evaluated motion with the design motion for real time damage evaluation will allow facility safety evaluation based on actual behavior. In this regard,

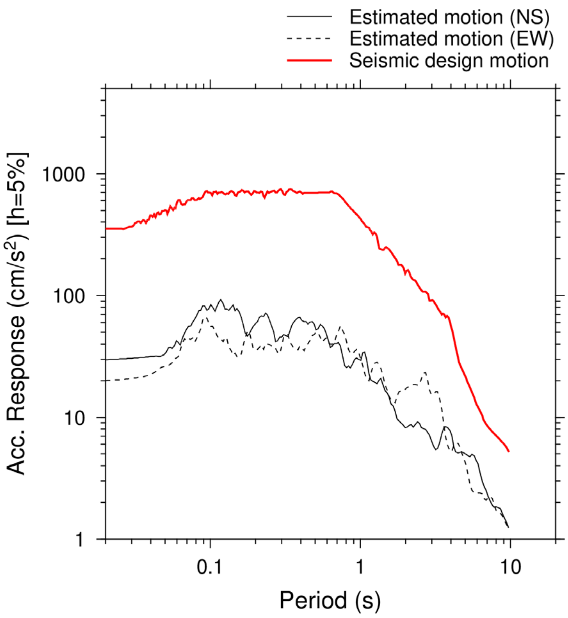


Fig. 12 Comparison of the acceleration response spectrum of the estimated wave during the 2016 Kumamoto earthquake with that of anticipated seismic ground motion in the design for earthquake countermeasures at the Oguchi site

the authors used a large-scale 3D elasto-plastic seismic response analysis method developed by Ichimura et al [7, 8]. Results from related research [4] indicated that it is possible to reproduce seismic response analysis evaluation. In future work, it will be necessary to expand functionality for the imposition of undrained conditions so that liquefaction analysis can be performed. However, the ability to conduct such three-dimensional analysis at the time of re-evaluation is promising.

This paper discusses long-term performance evaluation for ground where countermeasures have been applied, evaluation of input ground motion at a local site, and real-time damage evaluation based on seismic observation records from a tailings storage facility. With regard to monitoring technology, high-density observation using low-cost IoT-based accelerometers [9, 10] is currently being put into practical use, and measurement technology for the collection of data with high density and accuracy (e.g., optical fibers) is being developed. Monitoring is also being carried out, with the results being applied at operational tailings storage facilities for some of Europe's largest copper mines [11]. This research is expected to be useful for all-important safety monitoring at tailings storage facilities worldwide, as well as for real-time damage evaluation in the event of abnormalities such as earthquakes and application of rational measures in the field.

4. Conclusions

In this study, the authors examined three years of seismic records from large-scale slopes at an upstream-type tailings storage facility with wide-pitch lattice-pattern-walls type soil solidification applied as a liquefaction countermeasure. The findings are summarized below.

1) In line with the transfer function of ground response acceleration in the slope, ground improvement increased solidity by a factor of 2.9 to 5.5 as compared to the initial soil. The effectiveness of the countermeasure was maintained for 1.5 to 4.5 years after completion with no change in the transfer function.

2) The model for prediction of underground acceleration at the local site (based on the correlation between observation records of underground acceleration at the site and data from a nearby observation point as recorded by the National Research Institute) accurately reproduced actual reference records of observation

conducted at the site. Accordingly, if such a prediction model can be formulated from seismic observation records covering a certain period, basement acceleration at the local site can be accurately estimated from nearby observation records if observation of ground motion at the local site is interrupted.

3) Estimated ground motion using the prediction model during the 2016 Kumamoto Earthquake(April 16, Mj7.3) revealed a ground motion with a maximum acceleration of 30 Gal. The ground motion was much smaller than the design value. For real-time earthquake damage evaluation, facility safety can be judged immediately after tremors by comparing input ground motion estimated using the prediction model with the design value.

4) With the ability to evaluate tolerable seismic ground motion at the site via repeated simulation using an analytical model that represents observed seismic response, re-evaluation seismic ground motion values can be replaced with design values to improve the accuracy of safety evaluation. Such evaluation can be performed using large-scale three-dimensional elasto-plastic FEM seismic response analysis developed by the authors with high-performance computing technology. In the case of liquefaction analysis, it will be necessary to expand functionality for the imposition of undrained conditions.

This research is expected to be useful for all-important safety monitoring at tailings storage facilities worldwide, as well as for real-time damage evaluation in the event of abnormalities such as earthquakes and application of rational measures in the field.

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