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Special Contribution

Seismic Response Analysis of Ground/Geo-structures using Geo-Analysis Integration Code

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1. Introduction

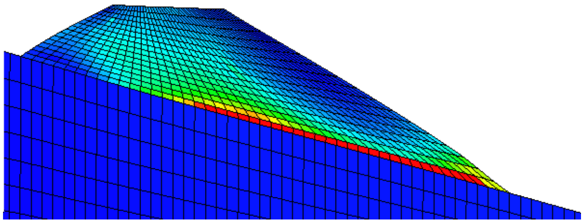
In the past, geo-analysis codes have been dedicated ones that have been used after deciding in advance what is expected to occur in the ground. For this reason, the inputs of the physical properties of the soils and the codes that were employed for the analysis differed depending on the engineering problem to be solved. For example, when a ground composed of alternating sand and clay layers was the target of analysis, the consolidation behavior of the ground was analyzed using a static code dedicated to consolidation of clay, with sand being treated as an elastic body. On the other hand, for analyzing the ground's seismic behavior, another code dedicated to liquefaction of sand was employed, with clay being treated as an elastic body. In order to newly establish soil mechanics by doing away with such provisional or makeshift measures, the Soil Mechanics Group of Nagoya University has been pursuing the development of an analysis code that would be capable of describing what would happen in the ground when it is subjected to a given form of external force by simply inputting at the beginning the initial conditions and the material constants of the ground. As a result of such development, we have proposed the SYS Cam-clay model (Asaoka et al., 2002) by incorporating the concept of sub-loading and super-loading surfaces into the Cam-clay model. This allows the constitutive equation of the soil skeleton to describe within a single theoretical framework the mechanical behavior of a wide spectrum of soils ranging from sand to clay as well as the infinite number of intermediate soils that exist in states between those of sand and clay (ALL SOILS). In addition, through further development in recent years, it has become possible to describe the combined loading state of the above model and the Drucker-Prager model (Drucker and Prager, 1952) through a "combined loading" elasto-plastic equation(Yamada and Noda, 2015) that we have proposed. Simultaneously, we have been developing the analysis code GEOASIA (Noda et al., 2008), which is based on finite deformation theory and is capable of handling problems of deformation and failure without distinguishing between the two (ALL STATES). This code is also capable of dealing with inertial forces, which allows handling of static and dynamic problems en bloc (ALL ROUND). Furthermore, following our studies on soil skeleton-water coupled analysis (2-phase analysis) of saturated soils (or soils assumed to be saturated), we have been extending the analysis code (Noda and Yoshikawa, 2015) to allow seamless handling of soil skeleton-water-air coupled 3-phase systems in states between unsaturated and saturated soils.

In Sections 2 and 3 of this paper, we introduce examples of analyses that have been or are currently being carried out on the seismic responses of grounds and various structures using the analysis codes for 2-phase systems and 3-phase systems. Using these codes to simulate fault movements, our group is also pursuing integrated analysis of the stages of earthquake occurrence and propagation as well as the effect of ground surface tremors on civil structures, considering these to be continuous mechanical phenomena. Although still at its initial stage, an example of analysis of strike-slip fault formation is introduced in Section 4. As for details of the elasto-plastic equation and analysis codes, please see references Asaoka et al.(2002), Yamada and Noda(2015) and Noda et al.(2008), Noda and Yoshikawa(2015).

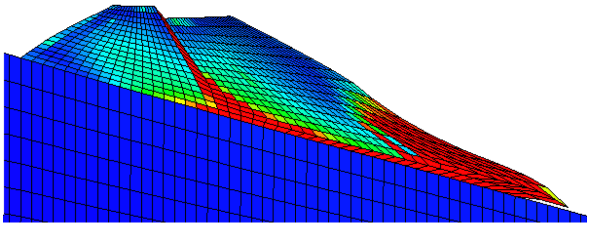
2. Seismic response analyses of ground considered as being saturated

2.1 Embankment collapse due to the 2007 Noto Peninsula Earthquake (Sakai and Nakano, 2012)

The 2007 *Noto* Peninsula Earthquake caused large-scale collapse of embankments built on sloped bedrock along the Noto Satoyama Expressway. Figure 1 is an example of analysis of one of the collapsed embankments. The material constants of the soil were determined by carrying out tests for determining the physical and mechanical properties of samples taken from the embankment slope, which was composed of tuff breccia. The earthquake motion that was observed at the K-NET Anamizu observation point was referred to when inputting the seismic wave to the bottom face of the sloped bedrock. The embankment was a relatively well consolidated one. During the earthquake, the embankment does not collapse because an increase in the mean effective stress and generation of negative excess pore water pressure occur within it simultaneously due to positive dilatancy behavior (i.e., hardening by plastic expansion), which results from the rapidly repeated large shear forces. After the earthquake, however, dissipation of the negative excess water pressure leads to water absorption, and collapse of the embankment occurs as a result of the softening behavior of the soil near the slip planes. The above is not just a singular case—there have been many other examples of delayed embankment collapse occurring a few hours or a few days after an earthquake.



(a) Immediately after earthquake occurrence

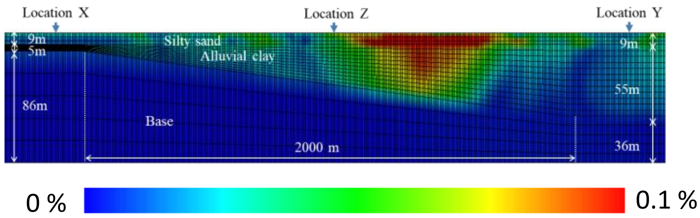


(b) 45 days after earthquake occurrence

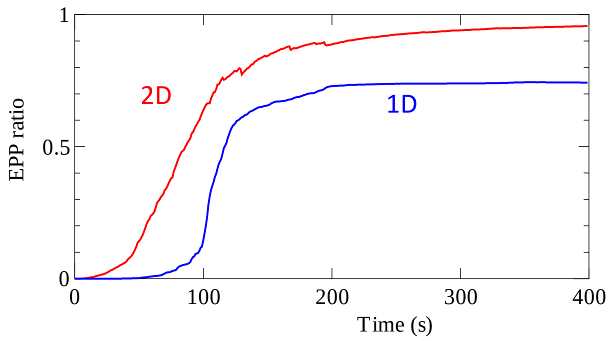
Figure 1 Delayed post-seismic collapse of an embankment built on inclined ground, Shear strain distribution

2.2 Extended ground liquefaction damage at Urayasu City caused by surface waves generated from the edge of sloped bedrock during the Great East Japan Earthquake (Nakai et al., 2015)

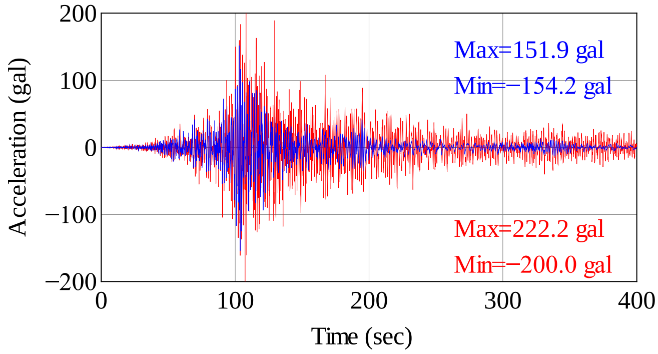
The off the Pacific coast of Tohoku Earthquake caused massive liquefaction damage over wide areas of landfill grounds along the coast of Tokyo Bay, including Urayasu City. Figure 2 shows an example of 2-dimensional plane strain analysis of a ground in Urayasu. The ground consists of a surface sandy soil layer and an alluvial clay layer below it, followed by bedrock (a diluvial layer), which slopes down from northwest (Location X, near Motomachi) to southeast (Location Y, near Shinmachi). The thickness of the clay layer is seen to increase as the bedrock slopes downward, and the analysis focused attention on this irregularity of the ground. The material constants and the initial conditions of the soils were determined from sand and clay test specimens sampled independently from the site and from the structure of the shear wave. The cross section for the analysis was modeled as a sloped diluvial stratum with a 5 m to 55 m thick layer of sedimented clay above it. The seismic wave that was input was 1/2 of that observed at a depth of about GL-36 m in Shinagawa. It was input as a rising wave to the bottom face of the diluvial stratum at approximately GL-100 m. Analysis using 1-dimensional modeling indicated that during the earthquake, the existence of the clay layer amplifies the seismic wave, particularly its long-period components. Although this causes the excess pore water pressure in the sandy layer to increase, liquefaction does not occur (Figure 2b). In contrast, 2-dimensional analysis showed that the seismic wave (body wave), the long-period components of which had become slightly amplified in the clay layer, interfere with the propagating surface wave (Rayleigh wave) (Figure 2d) that had been generated at the edge of the sloped bedrock (edge effect). In addition, aftershocks continued after the main tremor ceased (Figure 2c). For this reason, even in the surface layer that had been assumed to be a homogeneous material, non-uniform shear strain distributions are generated (Figure 2a), and liquefaction occurs over wide areas from Location Z (near Nakamachi) up to Location Y. The above computational results agree with the actual conditions of liquefaction damage that occurred in the Nakamachi and Shinmachi areas of Urayasu City.



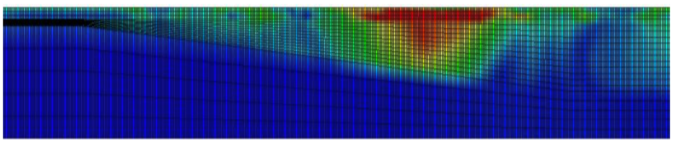
(a) Shear strain distribution 200 s after earthquake occurrence



(b) Excess pore water change at Location Z



(c) Acceleration response at Location



(d) Velocity vector diagram 50 s after earthquake occurrence

Figure 2 Seismic response analysis of ground on sloped bedrock in Urayasu City

2.3 Application of the Sand Compaction Pile (SCP) Method (Noda et al., 2011)

The SCP method is a well-known measure against liquefaction, and Figure 3 is an example of analysis of the mechanism of the resistance to earthquakes (suppression of deformation) obtained through SCP. The target of analysis was a ground of loose sand. First, the sand pile cavity expansion stage was simulated under the condition of axial symmetry, with consideration for the compaction of the ground around the pile. Following this, seismic response analysis focused on the characteristics of the composite ground was carried out using an SCP improved ground model containing the sand pile and the ground around the pile. In the SCP-improved ground, rapid undrained cyclic shearing occurs during the earthquake. This results in positive dilatancy behavior in the dense pile, which causes stress to concentrate in the sand pile, thus suppressing deformation of the ground. In the case of large earthquake movement (L2 movement), in addition to the above phenomena, even the sand between the sand piles that had been compacted at the time of construction of the sand piles exhibits positive dilatancy behavior, leading to dramatic suppression of ground deformation (Figure 3b).

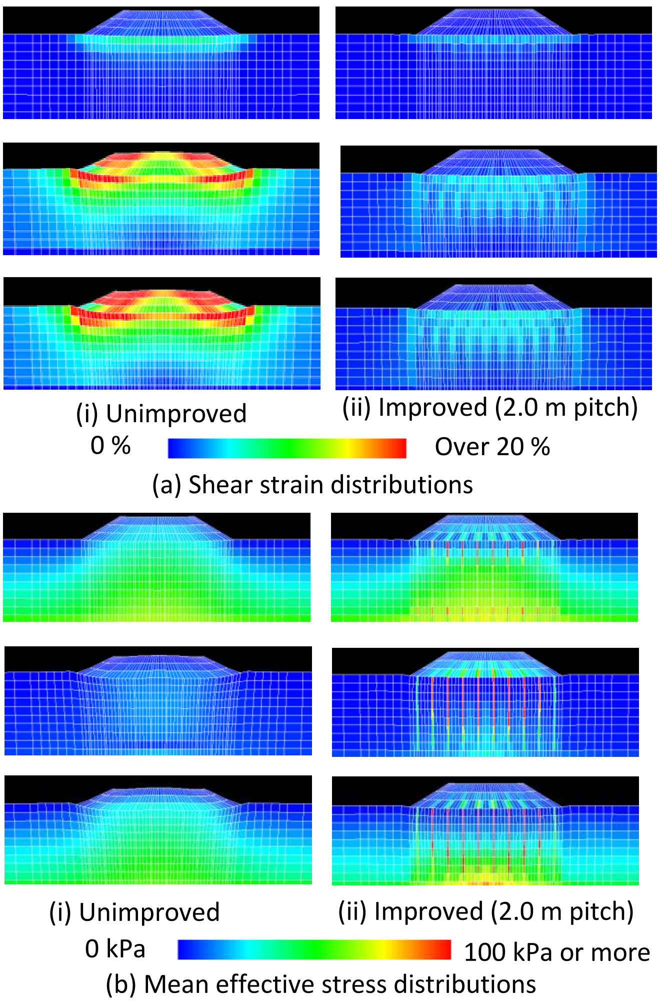


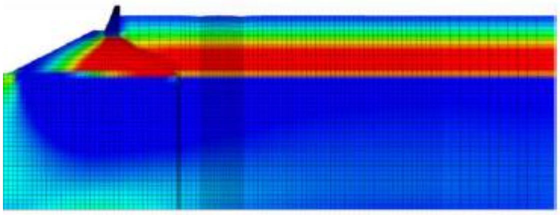
Figure 3 Validation of the SCP method (L2 seismic tremors), Upper: immediately before earthquake, Mid: 300 seconds after earthquake started, Lower: immediately after earthquake

2.4 Application of the Pore Water Pressure Dissipation Method for shore protection structures (Noda et al., 2015; Nonaka et al., 2017)

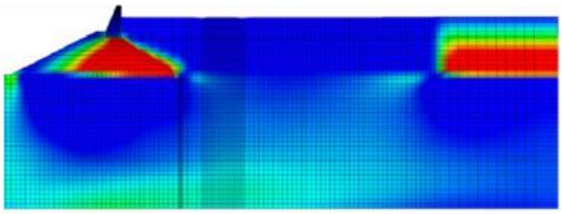
An example of a study on the effect of the Pore Water Dissipation Method as an anti-liquefaction measure with respect to man-made landfill ground with a shore protection structure within Nagoya Port is shown in Fig. 4. In this method, an important issue is the prediction of the amount of deformation due to the compaction that results from the suppression of increases in water pressure by drainage through vertical drains during an earthquake. Therefore, it is necessary for compaction and liquefaction, together with the amount of co-seismic compaction settlement and the amount of consolidation settlement that could occur after liquefaction, to be handled in an integrated manner. In order to avoid the enormous number of mesh partitions needed to represent the innumerable buried vertical drains and the surrounding ground, the macro-element method (Sekiguchi et al., 1986), which is used for analyzing compaction problems, was applied for the first time in this analysis. Furthermore, for evaluating the effect of well resistance, an extended macro-element method, which treats the water pressure in the drains within the soil elements as unknowns, was newly proposed and used (Yamada et al., 2015). It was observed that the increase in excess water pressure during an earthquake is suppressed if this method of improvement is applied to grounds with relatively high water permeability (Figure 4a). As a consequence, in marked contrast to non-improved ground, no liquefaction occurs in the improved ground, and the ground maintains its rigidity, thus suppressing localized settlement of structures built on the landfill. In addition, post-seismic consolidation settlement has been also inhibited because dissipation of excess water pressure has nearly ended immediately after the earthquake (Figure 4b).

2.5 Advanced development of the elasto-plastic constitutive equation of the soil skeleton—the combined hardening elasto-plastic constitutive equation (Yamada and Noda, 2015)

Upgrading the constitutive equation of the soil skeleton is indispensable for describing the behavior of a wide range of soils. In order to allow more accurate descriptions of cyclic mobility and other complex elasto-plastic behavior of soils under cyclic loading, a combined loading elasto-plastic constitutive equation (Yamada and Noda, 2015) was developed. This equation allows the SYS Cam-clay model (Asaoka et al., 2002) and the non-associated Drucker-Prager model (Drucker and Prager, 1952) to express combined loading states. Figure 5 shows the results of hollow cylinder torsional tests (upper figures) of liquefaction tests on Toyoura sand and simulation examples of this model (lower figures). In this figure, a, b, and c represent dense, medium dense, and loosely filled sand (having approximate relative densities Dr = 70%, 60%, and 45%, respectively). Although the set of material constants used consisted of only those of one group, it can be seen that it has been possible to describe the liquefaction tests of materials with differing densities in an integrated manner.

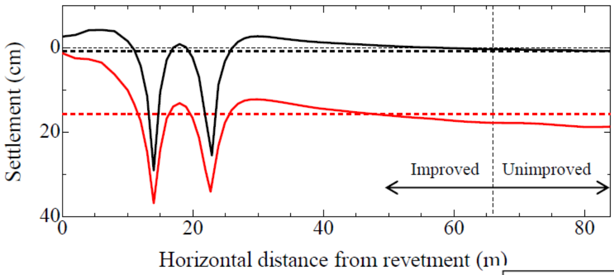


(i) Unimproved

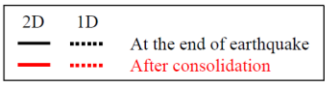


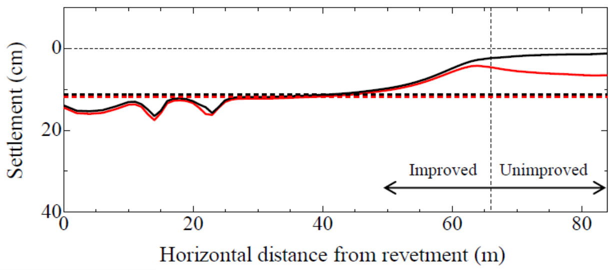
(ii) Improved (1.0 m pitch)

(a) Distribution of excess pore water pressure (when the earthquake ended)



(i) Unimproved

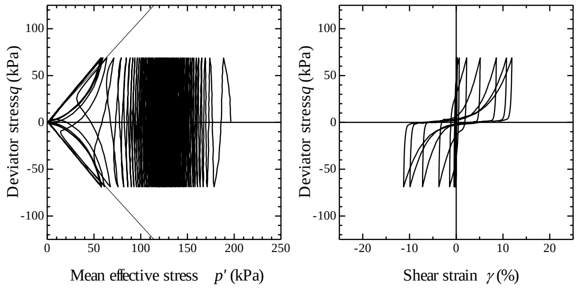




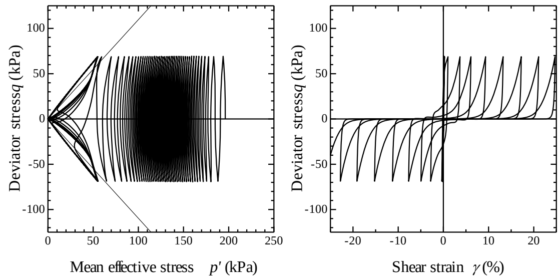
(ii) Improved (1.0 m pitch)

(b) Settlement of ground surface

Figure 4 Validation of the Excess Pore Water Pressure Dissipation Method

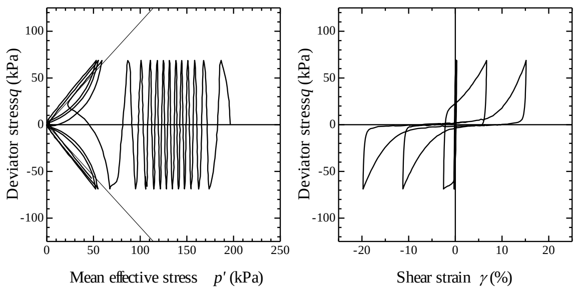


(i) Experiment

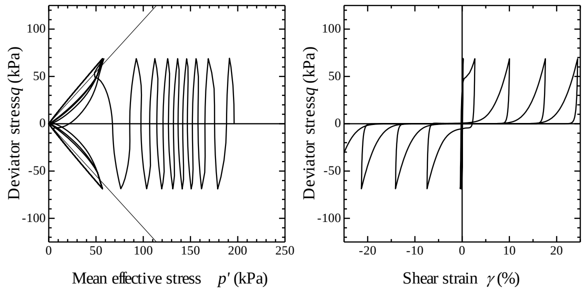


(ii) Simulation

(a) Dense sand (Dr≒70%)

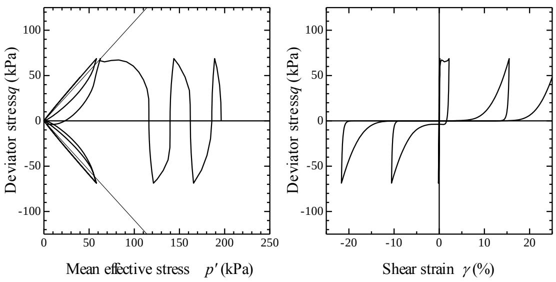


(i) Experiment

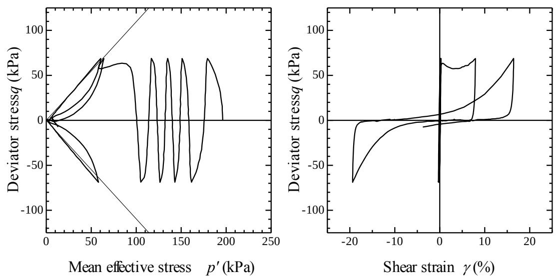


(ii) Simulation

(b) Medium dense sand (Dr≒60%)



(ii) Simulation



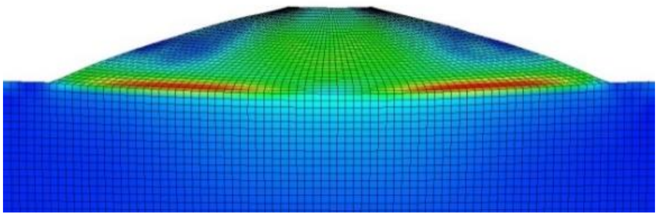
(i) Experiment

(c) Loose sand (Dr≒45%)

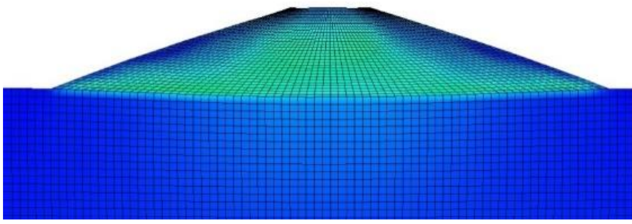
Fig. 5 Simulation of sand liquefaction tests by utilizing the advanced constitutive equation

3. Three-phase seismic response analysis that is also applicable to unsaturated soils

The Great East Japan Earthquake resulted in not only in the collapse/settlement of river embankments due to liquefaction of sandy grounds but also resulted in collapse of river embankments built on clayey grounds. This has been attributed to the liquefaction of an enclosed saturation area created at the lower parts of the embankment as a result of the consolidation settlement that takes place in clayey foundation ground during embankment construction. In addition, it has been confirmed that ground water levels in damaged cross sections were higher compared with those in undamaged ones. An example of the results of a 3-phase analysis study, which was carried out with focus on the effect of ground water level on the continuous behavior of an unsaturated soil embankment built on clayey foundation ground from the time of its construction up to the time of cessation of an earthquake, is shown in Figure 6 (Yoshikawa et al., 2016).



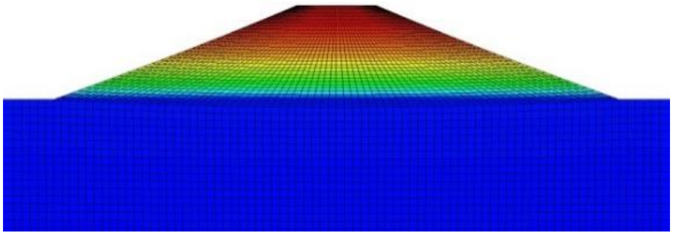
(a) Initial groundwater at the same level as the ground surface



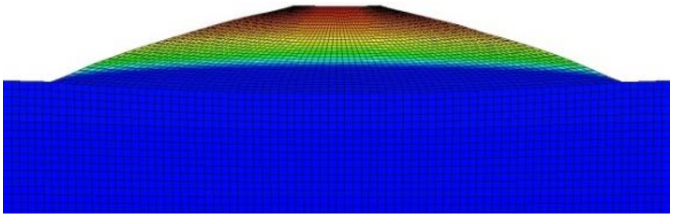
(b) Initial groundwater level at 2 m below the ground surface

Figure 6 Effect of groundwater level on deformation behavior of the river levee, Shear strain distribution (immediately after the earthquake)

The ground was configured on the basis of the results of mechanical tests carried out with undisturbed samples obtained from the disaster-affected Shimonakanome region inland of the Narusegawa River. The seismic wave that was input was a 1/2 wave based on the one that had been recorded at the KiK-NET *Onoda* observation point. The results showed that when the ground water level was high, the degree of saturation in the embankment was high and the skeleton forces (effective stresses) were small, resulting in large co-seismic deformation. Figure 7 illustrates analytical results showing the ground water level rising after the earthquake. If the ground water level is high, a phreatic line forms within the embankment after the earthquake and moves upward. After about a month, it moves down and returns to the original groundwater level. If the ground water level is low, although the phreatic line moves upward, it does not appear within the embankment even after the earthquake (data not shown). The reason for the upward movement of the phreatic line is the post-seismic dissipation of the excess pore water pressure/air pressure generated during the earthquake in the saturation area at the lower parts of the embankment and in the clayey ground.



(a) Immediately before the earthquake



(b) 1 month after the earthquake ended

Figure 7 Rise of the groundwater level after the earthquake

4. Analysis of associated strike-slip fault formation in ground surface layers

4.1 Analysis of associated strike-slip faults resulting from lateral strike-slip fault formation (Toyoda et al., 2019)

It is known that when lateral slip fault displacement occurs deep within a ground, complex slip bands referred to as flower structures (Riedel, 1929) are formed within the sub-surface ground layer immediately above the fault and that an array of echelon mode shear bands called Riedel shear bands appear on the ground surface. In lateral slip faults, it is quite rare for the slip fault lines to be straight lines. Generally, they are curved or include discontinuities (Fossen, 2016) called steps, as shown in Figure 8. The term “jog” refers to such locations that have deviated from the fault lines. Existence of a jog plays an important role in the process of formation of the flower structure. Figure 9 depicts the results of numerical analysis that takes account of the existence of a geometric barrier jog when numerically simulating Riedel shear bands. The solution yields associated strike-slip fault structures that possess the following characteristics:

(a) A fractal slip structure where global Riedel shear (colored green) encompasses localized Riedel shear (colored red)

(b) Secondary shear bands (P-shear) that are inclined to the left and are formed in between the right-inclined Riedel shear bands

(c) High-angle and low-angle shear bands (R-shear・R'-shear)

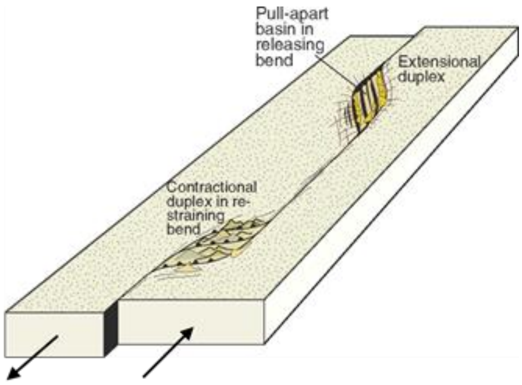


Figure 8 Left lateral strike-slip fault with step (Fossen, 2016)

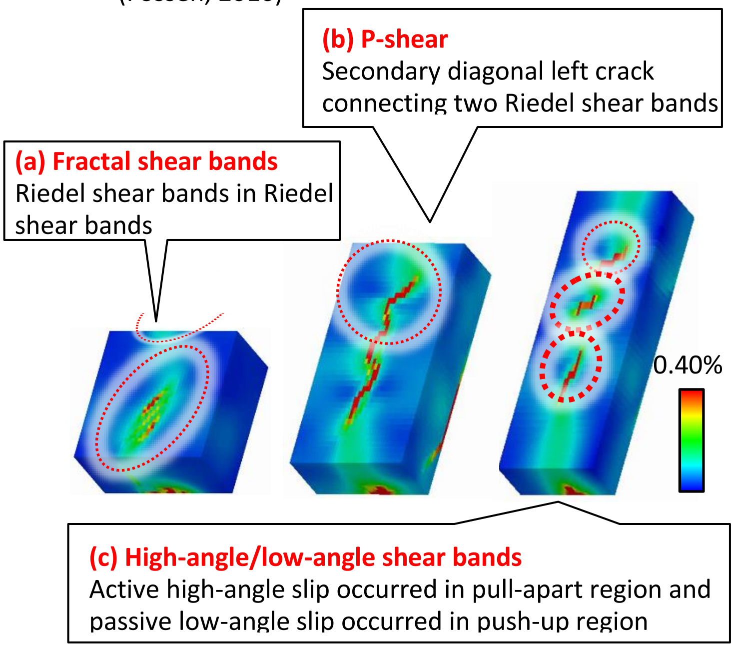


Figure 9 Characteristic associated strike-slip fault structures appearing at the ground surface, Shear strain distributions

5. Conclusion

We have endeavored to introduce, within the limited space available here, recent examples of seismic response analysis of grounds and earth structures using computational methods that are capable of describing in a consistent manner the behavior of the structures from their construction process before earthquake occurrence until after cessation of the tremors. Some of the new developments in tectonic geomorphology analysis have also been introduced.

In the field of strong motion seismology, analysis based on geomechanics of the trampoline effect (Asaoka et al., 2012) has gained a certain measure of recognition. However, there are still several issues, such as clarification of strong motion characteristics of unsaturated ground and pursuant analysis of the co-seismic and post-seismic behavior of natural/man-made slopes, the problem of water (torrential rain/tsunami) and earth structure interactions (Kodaka et al., 2015) that may lead to complex disasters, and the effects of aftershocks, that remain to be studied further. In order to elucidate these mechanisms, further deepening of geodynamics by embracing knowledge from related academic fields would be required.

As for the accuracy of analysis, it is needless to mention the importance of careful investigations through tests on models in which the boundary conditions and initial conditions are relatively well defined. In the case of actual problems, however, in addition to the heterogeneity of the ground, there is uncertainty about the seismic wave that is input as the external force, and there is no choice but to replace many of the 3-dimensional geomechanics phenomena with 2-dimensional problems. As a consequence, there are limits to accuracy, and wavering between optimism and despair just because of a few centimeters or a few tens of centimeters of quantitative accuracy would be a worthless effort. We believe that our immediate aim should be the development of analysis codes capable of extracting and giving us information on specific qualitative issues such as determination of the events that will take place in ground as a result of assumed external forces and determination of whether or not we have overlooked something in our designs.

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◆ A Brief CV of Dr. Akira Asaoka

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◆ A Brief CV of Dr. Toshihiro Noda

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