Numerical tests on formation mechanism of plate boundary décollement zone due to plate tectonics and earthquake-induced dynamic force

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ABSTRACT

In this paper, the influence of shear deformation happened in the process of the oceanic plate subducting beneath into the continental plate, and the dynamic force from earthquake on the formation of the décollement zone, a special horizontal plate boundary fault, is investigated with a specific numerical tests. The numerical tests are conducted with a static/dynamic soil-water coupling finite element-finite difference method (FE-FD) based on a sophisticated constitutive model in finite-deformation scheme. Particular attention is paid to the change of volumetric strain of the geomaterials in the proto-décollement zone that would become the décollement zone during the plate collision process. It is found that, a significant compressive volumetric strain would happen if the seabed rock has subjected to periodic earthquake loadings during twenty thousand years with a re-occurring period of every two hundred years. Amazingly, in spite of the fact that more than 20% of the volumetric strain happened, the structure of the material within the proto-décollement zone remains undisturbed, which is quite similar to the mechanical behavior of the décollement zone observed in the field. In other words, the cyclic loading might be one of the main reasons to form a fault zone (e.g., the décollement zone) with a much-higher density but keeping the random fabric structure intact.

Keywords: décollement zone, numerical tests, static shearing, cyclic loading

1 INTRODUCTION

Understanding the formation mechanism of the décollement zone is crucial important to clarify the mechanism of plate collision process and consequently may help to understand the mechanism of seismogenic zone. It is predicted with a high probability that a huge earthquake would happen in near future at Nankai Trough, a plate boundary fault in the Southwestern Japan. Understanding the mechanism may also help us to be able to take more suitable engineering countermeasures against the tsunami and liquefaction that mostly would happen in the earthquake. However, the basic mechanism and dynamics during the initiation and evolution of the plate boundary fault, the décollement zone, remain poorly understood, because researches related to huge earthquake are mostly based on the data from telemetry and the past geological records. Fundamental studies like laboratory tests and numerical tests related to the basic mechanical behavior of the décollement zone are then badly needed.

Ocean Drilling Program (ODP) and Integrated Ocean Drilling program (IODP) are recently conducted to drill into the plate boundary fault. ODP Leg 190 successfully penetrated the Nankai accretionary prism off Muroto: the drilling sites are located at the prism toe (Site1174) and reference site (seaward of the prism, Site1173), respectively. Previous studies revealed that muddy materials in the proto-décollement zone (e.g., Site1173), could keep a relative high porosity, since the random fabric structures are maintained by the cementation due to inter-granular bonding of authigenic clays. On the other hand, the cementation between the soil particles in the décollement zone (e.g., Site1174) collapsed and formed a fault zone with extraordinary dense material (Ujiie et al., 2003). These results indicate that the cementation formed by inter-granular bonding in the proto-décollement zone collapsed and the sediments shifted to a high-density state during the formation of the décollement zone. The décollement zone is mainly composed of brecciated fragments with a size up to several centimeters, within which the random fabric structure remains intact (Ujiie et al., 2003). In other words, the material within the brecciated fragments of the décollement zone did not experience any shearing even if it is in a denser state.

In geotechnical engineering, it is commonly acknowledged that the cementation or the structure (e.g., card house structure) existed in naturally deposited soils will collapse if it is subjected the shearing deformation. The above-mentioned phenomenon observed in the
décollement zone, however, contradict totally to this understanding. Therefore, it is necessary to find out other possible explanations for the phenomenon. Transient fluctuation of fluid pressure apparently occurred in the décollement zone due to very low frequency earthquakes is reported by Davis et al. (2006), which is similar to the description by Asaoka et al. (2002) that a cyclic loading may cause a large compression of weakly cemented soils. Based on this background, the authors here make a dramatic hypothesis that is totally different from the conventional idea. The hypothesis is that the cyclic loading both in isotropic and deviator stress due to stress wave propagation, especially P-wave during an earthquake, or fluctuation of fluid pressure and localized fracture failure, instead of shearing, cause the formation of the décollement zone.

In order to verify this hypothesis, static and cyclic loading tests for the proto-décollement and the décollement samples are conducted to identify the macro-scale deformation properties. These samples were taken by the Chikyu, a Japanese scientific drilling ship owned by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Unfortunately, we have to admit that it is not sufficient to discuss the formation mechanism of the décollement zone only by the laboratory tests, because the de-cementation process from the proto-décollement to the décollement at the collision boundary of the ocean and the continental plates is completely a boundary value problem (BVP). In this paper, in order to investigate the influence of shear deformation happened in the process of the ocean plate subducting beneath into the continental plate, and the cyclic loading due to stress wave propagation, especially P-wave during an earthquake, on the formation of the décollement zone, numerical tests were carried out with a static/dynamic soil-water coupling finite element analysis with the code name of DBLEAVES. The numerical calculation is in finite deformation scheme and the geomaterials are described by Cyclic Mobility Model (Zhang et al., 2007) in which the concept of rotational hardening is adopted. Particular attention was paid to the volumetric strain of the proto-décollement zone happened when subjected to dynamic force.

2 MECHANICAL BEHAVIOR OF SEABED ROCK SUBJECTED TO DYNAMIC FORCE

Generally speaking, seabed rock in seismic engineering and seismology is usually treated as a homogeneous elastic material when discussing the mechanical behavior during an earthquake and or in the subduction process of the ocean plate. In reality, however, a phenomenon similar to the fatigue fracture of metal was observed, in which the plastic deformation of an unconsolidated silstone increased abruptly when subjected to cyclic loading under a confining pressure of 5 MPa (Kurimoto et al., 2015). In field observation, it is also appropriate to regard the seabed rock as an elastoplastic material because the fracture and the fault slip of the seabed materials associated with the subduction of the plate in the décollement zone have repeatedly occurred. In order to check the influence on the mechanical behavior of the seabed rock from the dynamic loading (e.g., earthquake), numerical tests were carried out considering the elastoplastic properties of the materials. The changes of the volumetric strain, the structure and the stress-induced anisotropy of the seabed materials in the décollement zone were carefully investigated.

2.1 FEM mesh and boundary conditions

Fig. 1 shows two-dimensional (2D) finite element mesh used in the simulation, in which the subducting angle between the oceanic plate and the continental plate was assumed to be 2°, an average value at Nankai Trough. In the calculation, the material within the décollement zone whose thickness was confirmed to be 40 meters in the IODP program, was simulated with Cyclic Mobility Model (Zhang et al., 2007). In addition, the depth of the décollement zone was set to 390–640 meters by referring to the depth of the proto-décollement zone (e.g., Site1173) and the décollement zone (Site1174). The initial stress field was calculated by gravitational force.

![Fig. 1. FEM mesh and distribution of mean effective stress at initial gravitational stress field.](image)

![Fig. 2. Dynamic loading with sine wave.](image)

In the calculation, for simplicity, the dynamic loading was assumed to be a sine wave propagated from a distinct earthquake, applying in x direction at the depth of 1000 meters on the left side boundary of the
FEM mesh. Considering fact that the mean effective stress of the element where the loading point locates is 5.69 MPa, the maximum amplitude of the sine-wave of the point-loading was set to be 5 MPa and its frequency was 1 Hz, as shown in Fig. 2. In order to avoid any singular behavior that may happened in the calculation, the dynamic point-loading was applied on the node where an equal-displacement boundary condition in the horizontal direction was set to all the nodes along 320 meters surface around the loading point, noted in red line, as shown in Fig. 1. In the dynamic analysis, an initial-stiffness-proportional Rayleigh type damping was used and the damping coefficient was assumed to be 0.05, a common value for concrete materials or soft rock.

As to the boundary conditions shown in Fig. 1, the bottom of the domain was set to be fixed both in vertical and horizontal directions, while the two side boundaries were set to be free in the vertical direction. Meanwhile, the hydraulic boundary conditions of the bottom and the two side boundaries were set as undrained.

2.2 Materials parameters

It is commonly acknowledged that the material parameters of the geomaterials for numerical analysis should be decided based on laboratory tests. Yet, it is still very difficult to acquire the physical properties of the seabed rock and the sediments because the samples of the proto-décollement and the décollement are very difficult to obtain if considering the fact that only a couple of years ago people were just successful to obtain the precious core samples. The number of the sample pieces for the tests are therefore very limited. The material property of the proto-décollement zone, based on past experience, was estimated to be an overconsolidated but with high porosity and cementation, as pointed out in the works by Kurimoto et al. (2015). For this reason, in present study, the material parameters of the geomaterials were estimated based on the past experience and not determined directly from the laboratory tests on the geomaterial of the proto-décollement.

Fig. 3 shows the simulated element behavior of the imaged proto-décollement material under the confining pressure of 5 MPa. The detailed description of the model and the physical meaning of the material parameters can be found in the references (Zhang et al., 2007). From the simulated stress-strain relation in element tests shown in Fig. 3, it is known that a large negative dilatancy due to the collapse of cementation, which is the same as the mechanical properties of the décollement zone, is qualitatively described.

On the other hand, as the seabed rock is usually dealt with the elastic body in geology, seismology and geophysics, the continental plate and the ocean plate not including the fault zone, are also assumed as the elastic material in the numerical analyses.

If the huge dynamic force that represents the P-wave force from an earthquake were applied directly to the seabed rock, the material at the loading point would immediately reach the critical state, and the dynamic force energy could not propagate into the neighboring domain. Therefore, the elements with a thickness of 60 meters along the left side boundary of the FEM mesh were set to be a hard elastic rock material. The detailed values of the material parameters of all materials used in the simulation are listed in Table 1.

Table 1. Material parameters.

| Parameters | Continental plate | Oceanic plate | Soft rock | Loading position |
|------------|------------------|---------------|----------|------------------|
| Compression index $\lambda$ | - | 0.11 | - | - |
| Swelling index $\kappa$ | - | 0.0076 | - | - |
| Critical state stress ratio $\eta$ | - | 3.9 | - | - |
| Void ratio $N$ ($p^* = 98$ kPa on N.C.L.) | 0.70 | 0.70 | 0.70 | - |
| Poisson’s ratio $\nu$ | 0.20 | 0.20 | 0.20 | - |
| Young’s modulus $E$ (kPa) | 9.0E+5 | - | 1.95E+7 | - |
| Degradation parameter of overconsolidation state $m$ | - | 0.10 | - | - |
| Degradation parameter of structure $a$ | - | 0.25 | - | - |
| Evolution parameter of anisotropy $b$ | - | 0.0010 | - | - |
| Initial degree of overconsolidation $OCR$ (1/$R_0$) | - | 5.0 | - | - |
| Initial degree of structure $R_0$ | - | 0.010 | - | - |
| Initial anisotropy $\epsilon_a$ | - | 0.0 | - | - |
| Permeability $k$ (m/sec) | 1.0E-9 | 1.0E-9 | 1.0E-9 | - |
| Wet unit weight $\gamma$ (kN/m$^3$) | 21.07 | 21.07 | 21.07 | - |

Fig. 3. Simulated stress-strain-dilatancy relation in drained triaxial compression test under constant confining pressure of 5 MPa.

2.3 Test patterns

In this section, in order to identify the mechanical behavior of the décollement zone, particular attention was paid to the accumulation of the volumetric strain when the fault was subjected to periodic dynamic force of major earthquake with a loading time of one second in every two hundred years, lasted for twenty thousand years. In numerical tests, the results of the elements and the nodes in the décollement zone were carefully investigated. The distance from the targeted positions to the loading position is 310 meters, 910 meters, 1510 meters, 2110 meters, 2710 meters respectively in $x$ direction, as shown in Fig. 1.

2.4 Results and discussion

Fig. 4 shows the mechanical behaviors of the elements within 60 seconds experienced only one dynamic loading. Fig. 5 shows the results within twenty
thousand years when the dynamic force was applied repeatedly to the seabed rock in every two hundred years (totally hundred times). As shown in Fig. 4(b), the responding acceleration in y direction reached 7.0 m/sec$^2$, which is in the same order of the observed data in real earthquake motion. Therefore, it is possible to say that the dynamic loading used in the simulation is reasonably set. Due to the building up of the excess pore water pressure (EPWP) that reached 3.7 MPa, the effective stresses decreased substantially accordingly, as shown in Fig. 4. From these results, it is easy to understand that the viewpoint regarding the seabed rock as an elastic material in geotechnical engineering and seismology is not always correct and sometime it is necessary to model properly the seabed rock with suitable elastoplastic model.

It is known from Fig. 5 that the amplitude of the fluctuations in the effective stresses and EPWP at each element decreased gradually along with the increase of the repeated dynamic loading number. It is also known that the accumulated volumetric strain, as shown in Fig. 6, grew up to more than 20% within the décollement zone during twenty thousand years, which is quite similar to the observed data and verified the possibility suggested by the authors that the proto-décollement zone subjected to repeated dynamic force might give rise to a significant compression of the void ratio observed in the décollement zone.

Fig. 4. Mechanical behaviors of the elements within décollement zone (during 60 seconds).

Fig. 5. Mechanical behaviors of the elements within décollement zone (during twenty thousand years).

Fig. 6. Distribution of volumetric strain (after twenty thousand years).
structure, on the contrary, couldn’t be observed in the calculation. Here, it is needed to explain comprehensively that the structure is collapsed completely if the degree of the structure $R$ is equal to 1.0 (Asaoka et al., 2002). In other words, the structure and the stress-induced anisotropy within the décollement zone are maintained and no prominent change can be found, in spite of the fact that the volumetric strain has already reached up to more than 20%. This factor implies that the repeated dynamic loading due to periodic earthquakes, such as a P-wave earthquake shock, might be the reason to form the décollement zone. It should be pointed out, however, that the above-mentioned conclusion is still needed to be verified by accurate determination of the material parameters based on the laboratory tests using the core samples of the proto-décollement zone. Because the above mentioned calculation is conducted using the material parameters listed in Table 1, which were estimated based on experiences. Here again it is needed to point out that because the calculated results are strongly depend on the evolution rules for the collapse of the structure and the change of the stress-induced anisotropy, careful calibration of the material parameters is deadly needed. Further verification should be done in the next stage of the research.

3 MECHANICAL BEHAVIOR OF THE SEABED ROCK SUBJECTED TO SHEAR DEFORMATION

Though interesting results have been achieved in previous section, it is still difficult to say with confidence that the mechanical behavior of the décollement zone can be evaluated without taking account the shear deformation happened in the subduction process of the oceanic plate into the continent plate, in which the rate of the subduction is observed to be about 4 cm/year at the Nankai Trough. In this section, numerical test was also conducted to identify if the shear deformation happened in the subduction process of the oceanic plate would become one of the reasons to cause the formation of the décollement zone.

3.1 Test conditions

FEM mesh and material parameters, hydraulic boundary condition and the initial-stress field were totally the same as those in the previous section, with the only exception that in the previous section, the ground on the left side boundary of the FEM mesh was assumed to be a hard elastic rock. In this calculation, however, it is changed to an elastic material being the same as the continental plate and the oceanic plate. As to the boundary conditions, the top face and the two side boundaries of the continental plate were fixed, while the bottom of the oceanic plate was fixed in vertical direction. The two side boundaries of the oceanic plate were set as equal-displacement boundaries, also called as periodic boundary, in the horizontal direction. In order to reproduce the process of the oceanic plate subducting beneath into the continental plate in Nankai Trough, a given horizontal displacement with a rate of 4 cm/year in the horizontal direction was applied in both the side boundaries of the oceanic plate within the period of one thousand years (total 40 meters). Moreover, the given displacement with linear distribution was also applied periodically along the oceanic plate.

3.2 Results and discussion

Fig. 7 and Fig. 8 show the distributions of the deviator strain $\sqrt{2I_2}$ and the volumetric strain in seabed rock after subjecting to the imposed displacement of 40 meters (4 cm/year). Here $I_2$ is the second invariant of the deviator strain tensor. It is seen from these figures that the shear band occurred locally at the top of the décollement zone, which is in contact with the continental plate. The generated deviator strain within the shear band was more than 250%. On the other hand, the deviator strain was almost zero in the décollement zone outside the shear band. Now, let us focus on the mechanical behaviors of the elements within or outside the shear band in the décollement zone shown in Fig. 9.

![Fig. 7. Distribution of deviator strain (after one thousand years).](image1)

![Fig. 8. Distribution of volumetric strain (after one thousand years).](image2)

It is known from the figure that an extraordinary volumetric compression due to the collapse of the structure was observed in the shear band, while outside the shear band, the volumetric strain was still a very limited value that can contribute nothing to the densification of the brecciated fragments observed in the field survey. On the other hand, however, the structure and the stress-induced anisotropy outside the shear band remained virtually unchanged though it experienced somehow shear deformation. This
phenomenon indicates a fact that because the shear deformation is preferentially to happen within the shear band once the shear band was formed while the other region within the décollement zone will deform much less and consequently the random fabric structure is maintained. In other words, the above mentioned results imply that the shear deformation happened in the subduction process of the oceanic plate into the continental plate can hardly be the main reason for the formation of the décollement zone. There must be other factors that cause the dramatic reduction of the porosity within the proto-décollement zone.

On the other hand, however, these numerical tests were conducted with estimated parameters based on experience. Furthermore, some important properties, such as the influence of unsaturated/saturated condition, thermal and chemical effects in the long term are not taken into consideration yet. Therefore, further works should be done in near future, among which, first of all, the material parameters should be evaluated with accurate method based on the laboratory tests for the proto-décollement and the décollement samples that have already been obtained with Chikyu drilling. Meanwhile, the constitutive model should be extended to be able to describe the various characteristics of seabed rock under different unsaturated/saturated, temperature and chemical conditions.

**REFERENCES**

1) Asoaka, A., Noda, T., Yamada, E., Kaneda, K. and Nakano, M. (2002): An elasto-plastic description of two distinct volume change mechanisms of soils, *Soils and Foundations*, **42** (5), 47-57.
2) Davis, E. E., Becker, K., Wang, K., Obara, K., Ito, Y. and Kinoshita, M. (2006): A discrete episode of seismic and aseismic deformation of the Nankai trough subduction zone accretionary prism and incoming Philippine Sea plate. *Earth and Planetary Science Letters*, **242** (1-2), 73-84.
3) Kurimoto, Y., Yamamoto, Y., Sakaguchi, H., Zhang, F. and Saeda, Y. (2015): Mechanical properties of soft sedimentary rock under \( K_0 \) and isotropic cyclic loading conditions, *Proceedings of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*.
4) Ujije, K., Hisamitsu, T. and Taïra, A. (2003): Deformation and fluid pressure variation during initiation and evolution of the plate boundary décollement zone in the Nankai accretionary prism, *Journal of Geophysical Research*, **108** (B8), 2398-8-14.
5) Zhang, F., Ye, B., Noda, T., Nakano, M. and Nakai, K. (2007): Explanation of cyclic mobility of soils: Approach by stress-induced anisotropy, *Soils and Foundations*, **47** (4), 635-648.