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Numerical simulation of Riedel shear bands formation considering effects of geometrical barrier on strike-slip fault

Tomohiro Toyoda[1], Toshihiro Noda[2], Shotaro Yamada[1] and Akira Asaoka[3]

[1] Department of Civil Engineering, Nagoya University, Furo-cho, Chikua-ku, Nagoya, 464-8603, Japan.
[2] Disaster Mitigation Research Center, Nagoya University, Furo-cho, Chikua-ku, Nagoya, 464-8603, Japan.
[3] Association for the Development of Earthquake Prediction, 1-5-18, Sarugaku, Chiyoda-ku, Tokyo, 101-0064, Japan.

ABSTRACT

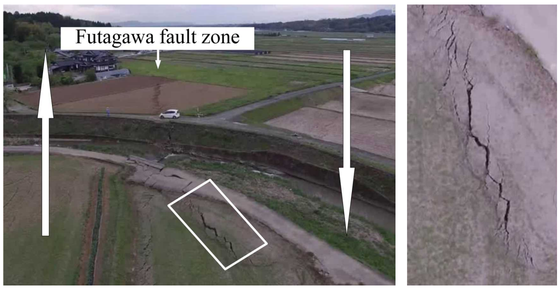
Displacements of strike-slip faults generate Riedel shear bands and flower structures at the surface ground above the faults. This paper aims to simulate deformation of strike-slip deformation of the surface ground considering jogs as geometrical imperfections. Analyses are based on the ***GEOASIA*** with SYS Cam-clay model that considers overconsolidation, which allows us to simulate softening behavior of brittle materials. Since the analytical results consider the presence of jogs, fractal shear zones (duplexes), P-shear, R/R'-shear, outer shear/splay shear, and tulip/palm-tree structures are successfully simulated. Furthermore, in terms of the scale effect, Riedel shear bands fractally appear when setting same overconsolidation ratio at the bottom of models.

Keywords: Riedel shear band; strike-slip fault; jog; elasto-plasticity; FEM

1 INTRODUCTION

Displacements of strike-slip faults generate echelon clacks called Riedel shear bands on the ground surface. Figure 1 shows an example of a Riedel shear band created along the Futagawa fault zone (right strike-slip fault) during the 2016 Kumamoto earthquake. The shear bands appear in various scales from small cracks such as example of Futagawa fault zone to the Transverse Ranges along the San Andreas Fault. While the former case is usually regarded as an evidence of strike-slip deformation for determine the location of a main fault, the latter case is an example of fault topography. It means understanding the mechanism of Riedel shear bands formation not only contributes fault displacement evaluation but also allows us to interpret the fault topography observed by geomorphologists.

When the Riedel shear bands appear on the ground surface, the multiple slip surfaces converge downward into a single strand in basement, therefore such blooming geometry inside the ground is named flower structure. Our former research (Noda et al., 2015) revealed that Riedel shear band can be simulated successfully by introducing material imperfection on the strike-slip fault zone. On the contrary, several researches (e.g. Woodcock and Fischer, 1986) reported that the existence of geometrical barrier called jog, i.e., fault plane deviation from the slip plane shown in Fig. 2, has an important role on the formation process of Riedel shear bands. In other words, discontinuous distribution of fault zone affects the development of



(a) Futagawa fault zone (b) Echelon cracks
Fig. 1. Subsidiary fault of Kumamoto earthquake (Geospatial Information Authority of Japan, 2016).

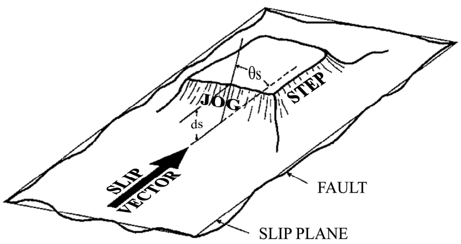


Fig. 2. Subsidiary fault.

Riedel shear bands. For example, Fig. 3 shows a left strike-slip fault with steps. When the jogs are pulled from both sides, shown in the back side of the figure, negative tulip flower structures similar to normal faults in a tensile stress field are formed, causing a local depression. On the contrary, when jogs are pushed from both sides, as observed near the side of the figure, positive palm-tree flower structures similar to reverse faults in a compressive stress field are formed, causing a local bulge. In structural geology, the former case, i.e., the tensile jog, is known as "pull-apart," while the latter case, i.e., compressive jog, is known as "push-up." This paper aims to simulate deformation of strike-slip deformation of the surface ground considering jogs as geometrical imperfections.

2 ANALYSIS CONDITIONS

Here, we attempt to understand the effects of jogs on Riedel shear and flower structure formation via elasto-plastic deformation analyses. Similar to a study by Noda et al. (2015), we use the deformation analysis code ***GEOASIA*** (Noda et al., 2008) loaded with the elasto-plastic constitutive equation from the SYS Cam-clay model (Asaoka et al., 2002). The results of this study are from the analysis of a single-phase system, which does not consider the existence of pore fluids.

2.1 Finite element mesh and boundary conditions

We use a 3D mesh (number of elements: 32,800), shown in Fig. 4. The y and z axes represent the running and vertical directions of a strike-slip fault, respectively. The dimensions are the same as those considered in a study by Noda et al. (2015). The model scale has a height of 5 cm following model tests designed by Ueta (2009). However, on the model's bottom face, vertical displacement is fixed. Then, we construct a bent (not straight) fault area and apply forced displacement (displacement velocity: $\dot{\delta}$ =10^{-6} m/s) in the y-axis direction at both ends of this area. With this model setup, area A experiences a pulling effect and becomes a pull-apart strain field, whereas area B experiences a compression effect and becomes a push-up strain field. For the side faces, the y–z face was set with non-friction conditions, whereas the x–z face had periodic boundaries, assuming an infinite region of periodic linkage along the running direction.

2.2 Material constants and initial condition

The material constants for the SYS Cam-clay model are listed in Table. 1, similar those considered in a study by Noda et al. (2015). The initial state of the soil skeleton structure assumes overconsolidation, which is the simplest state, with a uniform void ratio (e_0 = 0.57). When setting the parameters in Table. 1, the SYS Cam-clay model responds to drained triaxial compression, as shown in Fig. 5. In other words, the material is heavily overconsolidated soil, which exhibits obvious plastic expansion with positive dilatancy. Although the SYS Cam-clay model is a constitutive equation initially proposed to target soil materials, setting material parameters with a sufficiently small specific volume (extremely dense) enables the simulation of a brittle response, e.g., that of the rock material, which results in significant softening

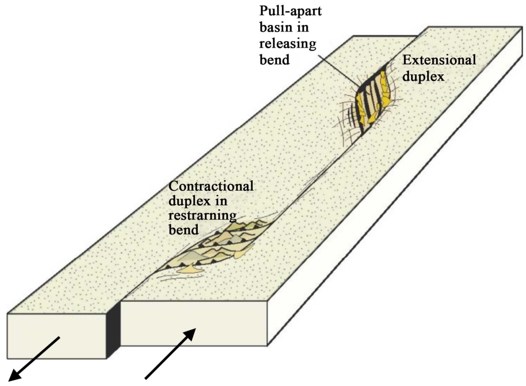


Fig. 3. Jogs on strike-slip fault (Fossen, 2016).

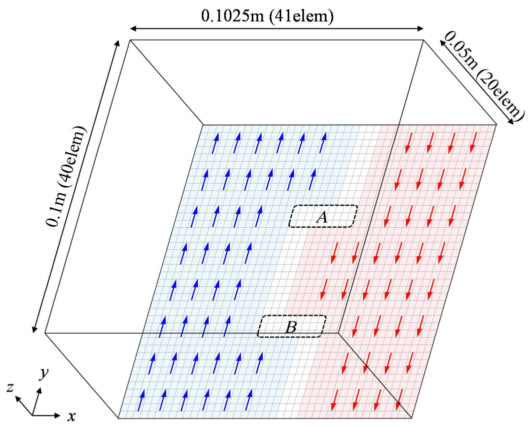


Fig. 4. Finite element mesh with jogs.

after the expression of peak strength. Figure 5 illustrates a soil response under confining pressure at middle depths of the model.

3 ANALYSIS RESULTS

For the model introduced in Fig. 4, the shear strain distributions at the final analysis stage are shown in Fig. 6(a). Furthermore, we enlarge the model scale by doubling and tripling the distance in the y-axis direction without modifying the number of interval elements between the push-up and pull-apart processes. Figures 6(b) and 6(c) show the results of the analyses in the double and triple scales, respectively.

3.1 Equal-scale model

For the equal scale model, we observe shear bands at the surface along the push-up side, as shown in Fig. 6(a). Furthermore, shear bands are characterized by a "fractal" shape, where the global shear band, shown in green, involves the local echelon-like strain (shown in red; since the computation includes "periodic boundaries" in the running direction, the green global shear band periodically links at the near side and back side of the model). Tchalenko (1970) and Barton and Larsen (1985) referred to the Riedel shear band fractal generation mechanism. Furthermore, Ueta (2009) conducted model tests using an artificial rock composed of a mixture of the Toyoura sand, gypsum, and water and confirmed that secondary shear bands formed after the formation of primary shear bands, as shown in Fig. 7. The results of the present study closely resemble those of experiments conducted by Ueta (2009). This multiplet structure is similar to a number of piled slates (blocks called horses) and is known as a "duplex" (Woodcock and Fischer, 1986).

3.3 Double-scale model

In the double-scale model wherein disturbance conditions at the surface are shown in Fig. 6(b), we observe that a shear band extends and connects multiple shear bands together, which are discontinuously strung. These are formed secondarily in a direction opposite to the Riedel shear. This type of crack is known as "P-shear" and was also observed in the shear band that formed during the Kumamoto earthquake (Fig. 1(b)).

3.3 Tripled-scale model

In the triple-scale model (Fig. 6(c)), we confirm that a shear band autonomously forms under tensile stress at a high angle to strike along the surface at the pull-apart side, whereas a shear band passively forms under compressive stress at a low angle to strike along the surface at the push-up side.

4 DISCUSSION

4.1 flower structure

Using Fig. 6(b) as a representative case, i.e, the double-scale model, the flower structure development processes are shown in Fig. 8. From phase (a) in the figure, while one shear plane continues to extend vertically on the push-up side (vertically spreading palm-tree structure), two shear planes with a jog between them continue to develop in a petaloid manner on the pull-apart side (horizontally spreading tulip structure). Later, in phase (b), the slip planes that extended from the deeper region in phase (a) reach the surface. Concurrently, shear strain appears locally at the ground-surface side. This phenomenon resembles splay development during the conditions of low confining pressure. In the final phase (c), these slip planes join together to form composite 3D slip plane structures.

4.2 angle of shear bands

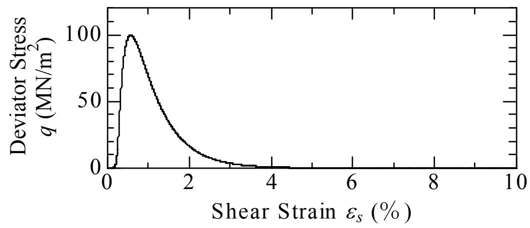
Although detailed information is not included in this paper due to a space constraint, It can be confirmed that the angle of shear bands above push-up/pull-apart jog corresponds the theoretical angle of R-shear/R'-shear estimated from Mohr-Coulomb criterion with analyzed principle stress on the ground surface. This result suggests that the jog strain fields, i.e., the difference between push-up and pull-apart, may be a factor that selectively produces shear faces that are conjugate with each other.

4.3 scale effect

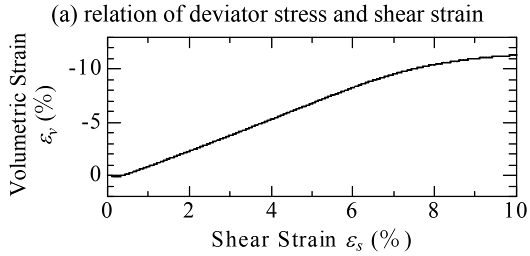
The shear strain distribution at the final analytical stage in the equal-scale model is shown again in Fig.

Table. 1. Material constants.

Elastoplastic parameters	
Compression index $\tilde{\lambda}$	0.0150
Swelling index $\tilde{\kappa}$	0.0002
Critical state constant M	1.0
Intercept of NCL N	1.7
Poisson's ratio ν	0.3
Evolution rule parameters	
Index for degradation of overconsolidation m	2.0
Physical property	
Density of soil particle ρ^s (g/cm³)	2.65



(a) relation of deviator stress and shear strain



(b) relation of volumetric strain and shear strain

Fig. 5. Jogs on strike-slip fault.

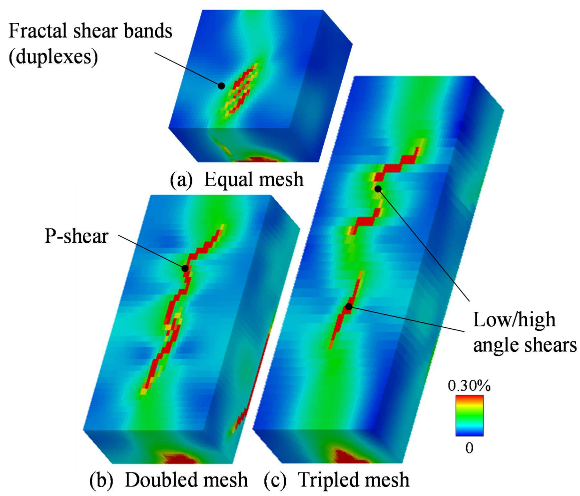


Fig. 6. Shear strain distribution.

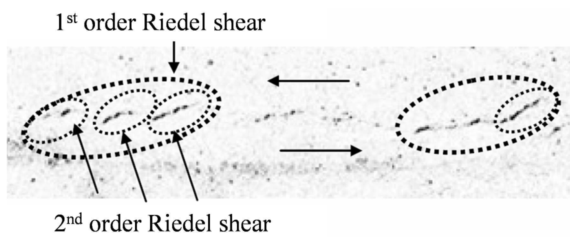


Fig. 7. Fractal shear (Ueta, 2009).

9(a). With this model as the basis, the entire model size and displacement rate are correspondingly 10, 100, and 1000 times greater. The results from these analyses are shown in Figs. 9(b)–9(d).

Figure 9 reveals that the large-sized models have only created a single Riedel shear on the surface. This originates when the material behavior becomes ductile, the softening rate reduces, and a splay phenomenon accompanied with divergence near the ground surface does not occur easily (i.e., the soil material nearing normal consolidation states due to increases in the soil-covering pressure in the large-sized models). In fact, for the other analyses with model void ratios that were adjusted to have overconsolidation ratios at the bottom face equivalent to the basic model, newly visible shear bands are similar to those of the basic model for all scales. This result supports the fractal characteristics of the Riedel shear, which have been proposed to “occur at various scales.”

3 CONCLUSION

The formation processes of subsidiary faults at the surface deposited along a strike-slip fault were solved using large-scale 3D elasto-plastic finite deformation analysis that considered the existence of “jog” as a boundary condition. The following results are obtained: 1) The existence of “jog” enabled the reproduction of the formation process of characteristic subsidiary fault structures, e.g., duplexes, P-shear, R-shear/R’-shear shear planes and palm-tree/ tulip structures. 2) The size effect was examined, and it was confirmed that by equalizing the bottom face overconsolidation ratios of the models, we solved the formation of similar shear bands at all the scales used in this study. This result supports the fractal characteristics of Riedel shear, which have been proposed to “occur at various scales.”

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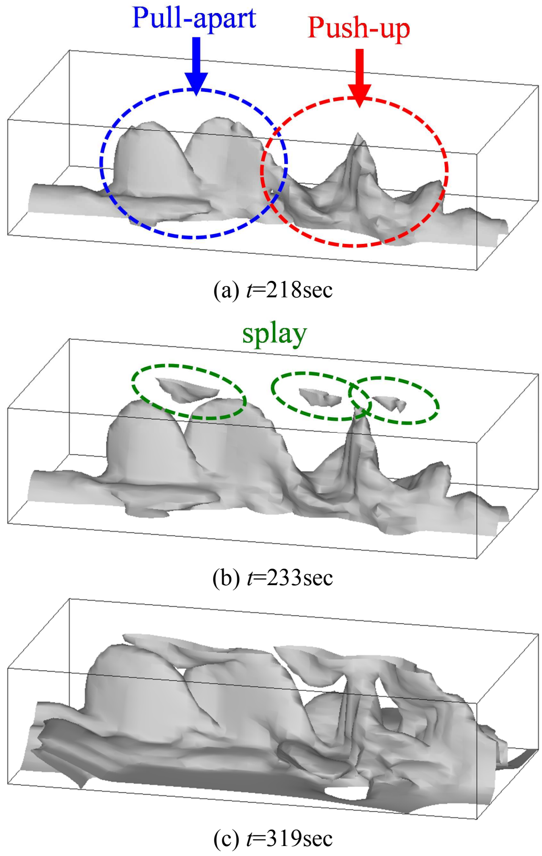

Fig. 8. Development of flower structure.

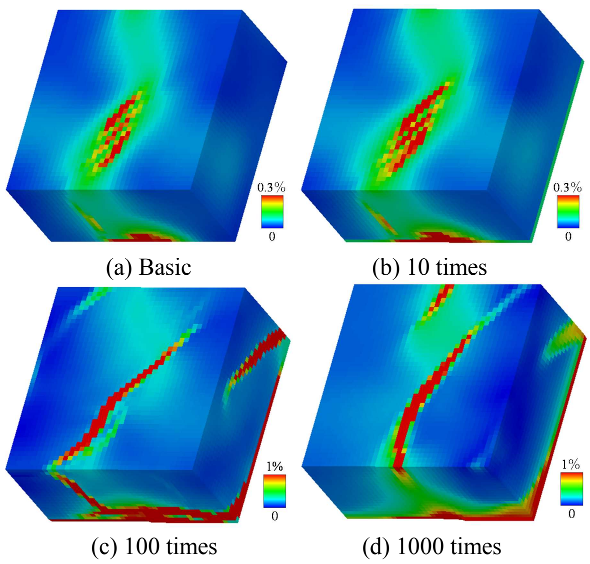

Fig. 9. Scale effect – shear strain distribution.

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