Riedel shear band formation with flower structures that develop at the surface ground on a strike slip fault

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ABSTRACT

In this paper, the formation of flower structures and the Riedel shear structures inside a ground above a strike slip fault were reproduced numerically using the soil-water coupled finite deformation analysis code **GEOASIA** that mounts the SYS Cam-clay model on it. The analysis results revealed that the Riedel shear structures accompanied by flower structures developed as a bifurcation mode triggered by initial imperfections showing plastic expansion with loss of overconsolidation on the shear bands.

Keywords: strike-slip fault, flower structure, Riedel shear band, strain localization, elasto-plastic analysis

1. INTRODUCTION

En echelon pattern shear bands called Riedel shear bands are known to appear via the covering stratum on the surface of a ground on a strike slip fault. In the case of right-lateral strike slip faults, shear bands appear in a left-handed en echelon arrangement as illustrated in Fig. 1 schematically. Such Riedel shear bands have been observed in terraced rice fields at Nojima Ezaki during the 1997 Southern Hyogo Prefecture Earthquake (Photo 1). Numerous modeling experiments, as typified by the work of Naylor et al. (1986), have been carried out in the past with the aim of simulating Riedel shear band formation. Visualization of the flower structure formed due to a strike slip fault and its propagation from the fault plane in the basement through the covering stratum up to the ground surface to create Riedel shear bands has been studied by Ueta (2003) using X-ray CT scanning.

The authors have developed the soil-water coupled finite deformation analysis code **GEOASIA** (Noda et al., 2008) mounted with the SYS Cam-clay model (Asaoka et al., 2002) elasto-plastic constitutive equation, which incorporates the effects of the soil skeleton structure, and it has been employed by the authors in the past to deal with the phenomenon of ground failure by considering it to be progressive failure due to strain localization. In contrast to analyses that require a given slip plane to be set up beforehand, the authors' studies have been targeted mainly at examining where in the ground strain localization occurs and how such strain localization propagates through the ground both spatially and temporally (Asaoka et al., 1994; Asaoka

Fig.1. Pattern diagram of Riedel shear band formation and flower structures (Tani et al., 1997).

Photo 1. Riedel shear band formation observed in terraced rice fields at Nojima Ezaki during the 1997 Southern Hyogo Prefecture Earthquake (Nakada and Okada, 1999).

and Noda, 1995; Noda et al, 2005). In this paper, numerical simulation of the formation of flower structures and Riedel shear bands within a ground on a strike slip fault is attempted through use of the above analysis code mounted with the constitutive equation that allows accurate replication of the mechanical behavior of ground materials.

2 SIMULATION OF FLOWER STRUCTURE FORMATION

2.1 Conditions of analysis

The analysis performed with the aim of simulating flower structure formation is described first. The conditions of analysis were decided by referring to the experimental work carried out by Ueta (2003) using a model. The finite element mesh and boundary conditions used in this analysis are shown in Fig. 2. Three-dimensional analysis was performed using a 2-dimensional mesh with one finite element placed in the strike direction (y direction) of the fault. The 3 elements at the bottom end of the central part were made to represent the fault zone, assuming a right lateral strike slip fault. The boundary conditions assigned are described below. In the vertical planes (x - z planes) that face each other in the y direction, periodic boundaries were assigned to the parts immediately above the fault. For the other parts, uniform forced displacement (constant speed rate 10^{-6} m/s) was assigned along the y direction across the fault zone in a reversed manner (i.e., in a direction assuming a right lateral strike slip fault). In addition, the x - z and y - z planes were assumed to be in a frictionless state. The material constants used in the SYS Cam-clay model were close to those of the same sand used in a previous study concerning calculation of drained bearing capacity (Yamada et al., 2009). The initial values assigned were no initial structure ($R^*_0=1.0$), no initial anisotropy ($\zeta_0=0.0$), an initial state of isotropic stress ($K_0=1.0$), and an initial specific volume v_0 of 1.57. Under these conditions, the soil under study is in a heavily overconsolidated state ($1/R_0=1.3 \times 10^6$ to 3.1×10^7 ; the nearer the ground surface, the greater the overconsolidation). When the above material constants and initial values are employed, the SYS Cam-clay model shows that drained shear causes hardening due to

Fig. 2. Finite element mesh and boundary conditions.

plastic expansion to take place at relatively low strain levels, after which the shear stress q reaches a peak and softening occurs.

2.2 Results of analysis

Figure 3 shows the distributions of the shear strain, overconsolidation ratio, and change in specific volume after the shearing progressed to a sufficient extent. Shear bands (strain localization) originated from the fault zone at the bottom end of the ground. A flower structure in the form of an upwardly convex logarithmic spiral directed toward the upper region formed as the strike slip increased. Furthermore, it can be recognized from the distributions of the overconsolidation ratio and change in specific volume that hardening due to plastic expansion resulted from the loss of overconsolidation that occurred in the soil elements on the shear bands.

Fig. 3. Simulation of flower structures

3 SIMULATION OF RIEDEL SHEAR BAND FORMATION WITH A FLOWER STRUCTURE

3.1 Conditions of analysis

The analysis performed using a 3-dimensional mesh with element breakdown in the y direction in order to simulate Riedel shear bands with a flower structure is described next. Again, the scale and other conditions

were decided by referring to the experimental work carried out by Ueta (2003) using a model. The finite element mesh and boundary conditions used in this analysis are shown in Fig. 4. It was assumed that the y - z lateral planes were frictionless walls and that the displacement in the x direction was kept fixed. At the bottom face, the displacement in the z direction was kept fixed, and uniform forced displacement (constant speed rate 10^{-6} m/s) was assigned along the y direction across the fault zone in a reversed manner (i.e., in a direction assuming a right lateral strike slip fault). Periodic boundaries were assigned to the x - z lateral planes and conditions were set so that the same pattern continued in the y direction. (In the analysis described earlier in Section 2, forced displacement was assigned to the x - z planes by a velocity boundary except for the area immediately above the fault. The current analysis differs from the earlier one in this respect.) Additionally, in order to manifest the bifurcation mode due to initial imperfections and induce strain localization (Asaoka and Noda, 1995; Noda et al, 2005), the material constant N (NCL intercept) of only those soil elements of the fault zone at the bottom end was made different (the initial overconsolidation ratio becomes different as a consequence) so as to produce an initial imperfection. By showing at the beginning the results of analysis in the case of a ground without an initial imperfection, it becomes possible to debate the effects of initial imperfections that produce Riedel shear bands.

Fig. 4. Finite element mesh and boundary conditions.

Fig. 5. Shear strain distribution (without initial imperfection)

3.2 Results of analysis

Figure 5 shows the shear strain distribution at the surface of the analyzed region in a ground without an initial imperfection (please note that the length of the analyzed region in the x direction is half of that shown in Fig. 4). When there is no initial imperfection in the ground, only flat-lying shear bands are formed even if slip occurs at the bottom face, and there is no appearance of flower structures or Riedel shear bands.

The shear strain distributions at the surface of the analyzed region in a ground with an initial imperfection are illustrated in Fig. 6. It can be seen that assigning an initial imperfection to the ground makes Riedel shear bands appear on the ground surface along with the increase in relative displacement at the bottom face. Figure 7 shows the equi-shear strain distribution within the ground. A flower-shaped strain localization region that twists and develops as it travels obliquely across the fault can be identified within the ground. It can be seen from Fig. 6 that the Riedel shear bands in a left-handed en-echelon arrangement are formed when this flower-patterned strain localization region reaches the ground surface. The shear strain distribution at the cross section indicated by the dashed lines in Figs. 6(b) and 7 is depicted in Fig. 8. It can be seen that a number of flower structures have developed that are directed toward the ground surface. Figure 9 shows the shear strain distribution with the deformation magnified 200 times. Protrusions, which are characteristic of Riedel

(a) Relative displacement 0.12mm

(b) Relative displacement 0.45mm

Fig. 6. Shear strain distribution (with initial imperfection)

shear bands, can be seen to have formed near the ground surface due to the positive dilatancy exhibited by the heavily overconsolidated soil on the shear bands. The above results show that use of finite deformation analysis incorporating the constitutive equation of the soil skeleton that describes the changes in the skeleton structure (the loss of overconsolidation is important in the case of the present calculations) makes it possible to simulate, as a progressive failure phenomenon caused by strain localization, the formation of Riedel shear bands with a flower structure.

Fig. 7. Contour surface ($\varepsilon_s = 0.005$) of shear strain (with initial imperfection)

Fig. 8. Flower structures (with initial imperfection)

Fig. 9. Uplift of ground surface: the deformation magnified 200 times (with initial imperfection)

4 CONCLUSIONS

The process of formation of shear bands on the surface of a ground on a strike slip fault was dealt with as a progressive failure phenomenon that results from strain localization in this paper and was simulated using the ground analysis code **GEOASIA**. As a result, it was shown that Riedel shear bands with a flower structure are formed as a bifurcation mode that is induced by initial imperfections in the ground. It was also shown that (plastic) expansion occurred on these shear bands due to the loss of overconsolidation.

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