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The Effect of Lower Detachment Zone on Buckle Folds Geometry

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Abstract

Buckle folds are common traps for hydrocarbon in several contractional provinces. Buckle folds form where stratified sequences rest a top salt or some other utterly weak rock as a decollemet zone in units with high competency contrasts by a compressive stress which acted along the length of the rock layers. An important parameter affecting buckle folding of a competent zone above a mobile decollement is existence of a thick lower decollemet. In this paper the effect of detachment zone on folding of rock layers is studied using finite element method. Large deformation formulation is considered. Mohr-Coulomb plasticity model is used to deal with nonlinearity of material during folding. Two cases of folding are considered. In the first case a symmetric fold with equal detachment thickness beneath two flanks is analyzed. In the second case detachment zone is omitted in one flank. Finally, the effect of detachment zone on folding and deformed shape of buckle fold is studied.

Key Words: Buckle folds, Numerical modeling, Finite element method, Detachment zone, Folding.

1. Introduction

Buckle folding is a natural deformation process that has received much attention by structural geologists. Buckle folds form where stratified sequences rest a top salt or some other utterly weak rock as a decollemet zone in units with high competency contrasts by a compressive stress which acted along the length of the rock layers [1]. There are more than 12 folds and thrust belts in the world that have been shortened above an evaporitic substrate acting as a viscous decollement [2-3]. The shape of Buckle folds depends entirely on the physical-mechanical properties of the layers. With increasing shortening a transition in deformational behavior may resulted in forming of faulted detachment folds [4]. When geometric characteristics and overall form of the folds are forced on the layers by virtue of the orientation and form of the faults with which the folding is associated, the beds are not free to fold and they just go along for the ride and sometimes stretch or bend examples of this mechanism are fault-bend folds and fault propagation folds. Fault-bend folds are formed when beds are displaced along thrust faults with ramp-flat geometries. Fault propagation folds shape is determined by fault shape. In this case the ramp does not tie into an upper flat but is replaced upward by on asymmetric fold, which is overturned in the direction of transport [1]. In fact, faulted detachment folds are transition of detachment folds to fault-propagation folds [4].

Fold development has been studied using analytical solutions [5-6], physical analogue models [7-8] and numerical methods. The analytical approaches are valid for the initial phases of folding. The development of folds to finite amplitude can be studied by physical analogue models or numerical methods but only numerical models give quantitative results for stresses due to shortening. Numerical methods are based on two approaches: kinematic and mechanical modeling. In kinematic approach, development of fold is explained based on geometric constraints such as conservation of line length, bed thickness and cross sectional area [9-12]. One key drawback of kinematic model is describing deformation a priori and approximating complexity of detachment-fold growth in space and time [13]. In the other hand, mechanical approach allows investigation of the control of mechanical stratigraphy on the styles and kinematics of detachment folding.

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Mechanical model has proved a useful tool when high strains have to be reached. Parrish et al. used non-linear temperature-dependent viscosity to simulate similar folding [14,15]. Effect of viscosity contrast was considered by Stephansson [16]. De Bremaecker and Becker included gravity in the models for diapiric structures [17]. Elasto-viscous and elasto-plastic rheologies for the buckling of single layers were used by Zhang et al.[18]. Pena and Catalan developed a computer program to simulate the process of natural folding from small to large scales based on elasticity equations [19]. Hardy and Finch used discrete-element method to investigate detachment folding [20]. Sanz et al. combined non-linear finite element model with large deformation frictional contact to study fracture evolution during folding [21]. They showed that the results of the finite element model compared well with selected field observations.

An important parameter affecting buckle folding of a competent zone above a mobile decollement is decollemet thickness. Because analytical solutions are generally limited to small deformations and simple geometries, numerical simulations are necessary to understand the physics and mechanics of geological processes such as folding. In this paper the effect of decollement on folding of rock layers is studied using finite element method as a powerful numerical tool. Large deformation formulation with Mohr-Coulomb plasticity model is used. It will be shown that different decollement thicknesses beneath the flanks of a fold can result in formation of a nonsymmetric detachment fold.

2. Finite Element Model

Buckle folding can be studied considering continuum mechanics to relate forces to displacement of folding media and can be modeled numerically using finite element method. Nonlinear geometry and material can be handled appropriately in this method.

In this study it is assumed that a section consists of strong and soft layers under tectonic forces is folding. A two-dimensional finite element model of the anticline has been constructed (Figure 1). As shown in this figure, an initial curvature is assumed for the model. To reduce the number of elements, and thus the computation time, the size of the elements is increased away from the region of interest (the fold). This has led to a total of almost 1500 elements. The used elements are 4-node, with linear shape functions and thus constant strain and stress. In all models the upper surface is free to deform horizontally and vertically. The lower surface lies on springs resembling the mobile decollement. The springs are active only in compression. In order to subject the anticline structure to a horizontal compressional stress field, a horizontal shortening is applied to the left vertical edge while the right vertical edge has zero vertical and horizontal displacements. The sequence of rock layers are chosen based on core data from a well at the crest of structure. The material properties of the layers incorporated in the numerical models are divided into two material categories of strong and weak listed in Table 1. The sequence of strong and soft layers from top is given in Table 2 according to well core data. As elements experience large rotations as well as large strains, a large deformation formulation is used. Mohr-Coulmb plasticity is assumed for both strong and soft materials. Plain strain 2D finite elements are used throughout this study.

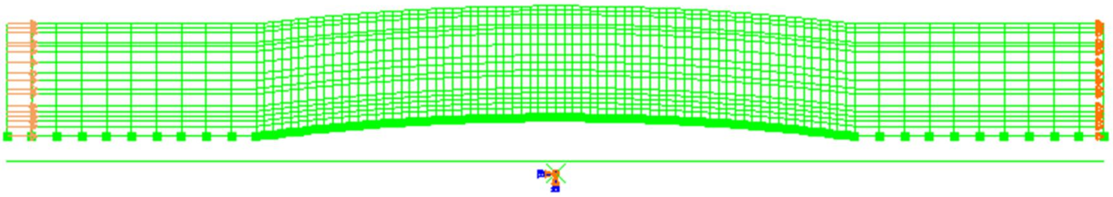

Figure1- Elements and boundary conditions

Table 1. Rock properties

Category	Young's modulus (GPa)	Poisson's ratio	Density (kg/m3)	Friction angle	Cohesion (MPa)
Strong	50	0.25	2500	30	5
Soft	25	0.15	2500	10	1

Table 2. Rock properties

Number from top	Material type	Thickness(m)
1	Strong	350
2	Soft	530
3	Strong	1105
4	Soft	275
5	Strong	330
6	Soft	710
7	Strong	200
8	Soft	200
9	Strong	800

3. Modeling Results

To show the effect of detachment depth on folding, first a uniform 1000 m detachment depth is assumed beneath the rock layers. This was modeled by definition of a rigid surface at the depth of 1000 m beneath the model. Fig. 2 shows the von Mises stress in deformed shape of the fold. As shown in this figure the strong layers bear more stress than soft layers, but as shown in Fig. 3 the maximum in plane principle plastic strains are concentrated in two shear bands which cross both soft and strong layers. The shear bands are symmetric about fold axes and show the location of fault development during folding. Additionally, deformed shape of the fold if symmetric about fold axes and two limbs attach the bottom rigid basement. It shows that development of fold requires synclines to be induced.

Second analysis is devoted to variable detachment depth beneath two limbs of the fold. Fig. 4 shows the geometry of rigid surface with 1000 m depth beneath straight part of the left limb and zero depth beneath the straight part of the right limb. Fig. 5 shows von Mises stress in deformed shape of the fold and Fig. 6 shows maximum in plane principle plastic strain in this case. As shown in this figures, the final shape of the fold is not symmetric anymore and plastic strains are concentrated in the hanging wall of the fold where a detachment zone exist. A small fault also develops in footwall. In spite of first case, the left limb does not attach the bottom rigid surface in this case.

4. Conclusions

In this paper, the effect of detachment zone on folding of rock layers was studied using nonlinear finite element method. Large deformation (large strain and large rotations) formulation was considered. Mohr-Coulomb plasticity model was used to deal with nonlinearity of the material for different rock layers during folding. Two cases of folding were considered. In the first case a symmetric fold with equal detachment thickness beneath two flanks was analyzed. In the second case detachment zone was omitted in one flank. It was shown that detachment zone affects deformed shape of the fold and location of induced plastic strains during folding. In the first case two faults (concentrated plastic strains) were form in two flanks of the fold symmetrically, but in the second case a large fault was formed in the flank above the detachment zone and a small fault was formed in the flank without detachment zone.

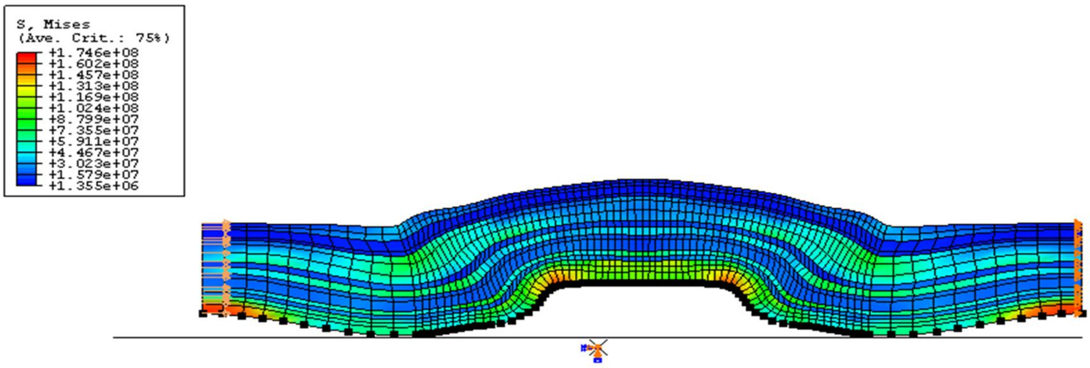

Figure 2- Von Mises stress (Pa)

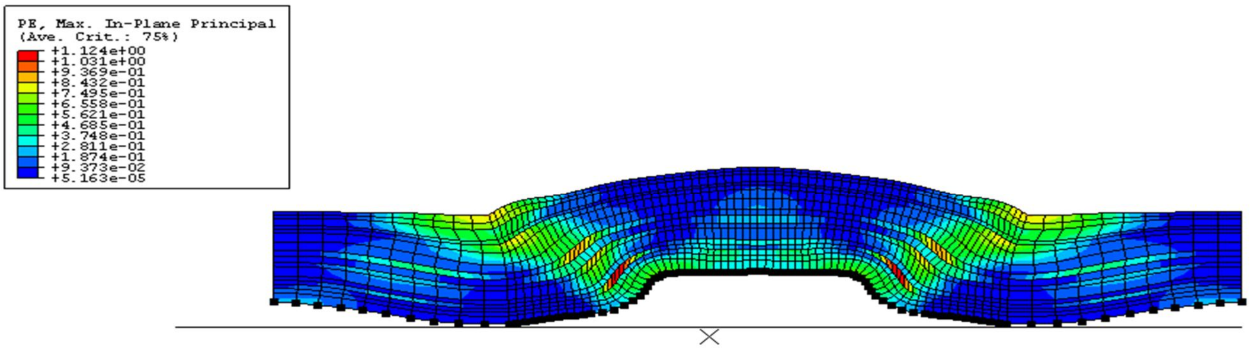

Figure 3- Max in-plane principle plastic strain

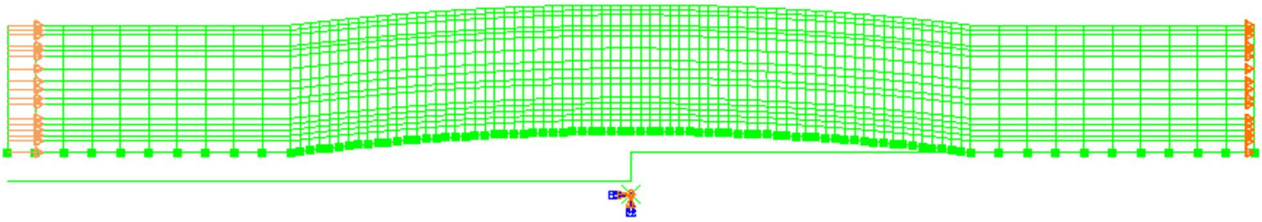

Figure 4- Elements and boundary conditions (case 2)

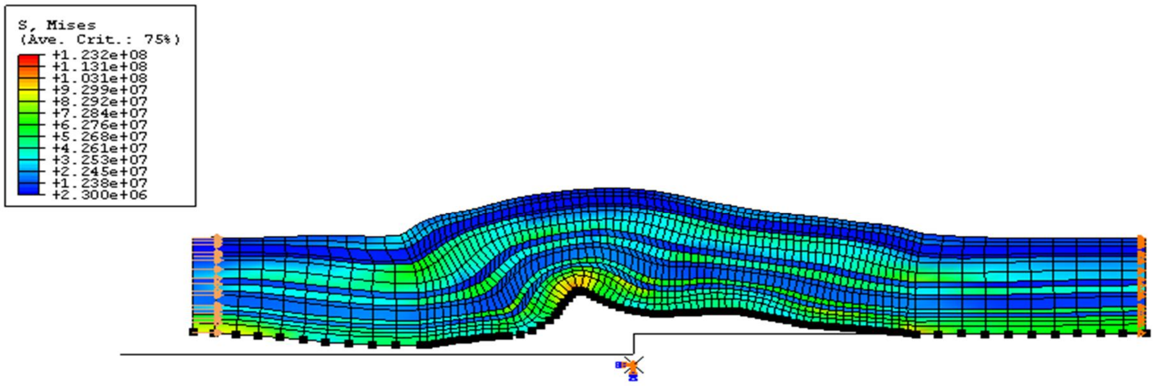

Figure 5- Von Mises stress (Pa) (case 2)

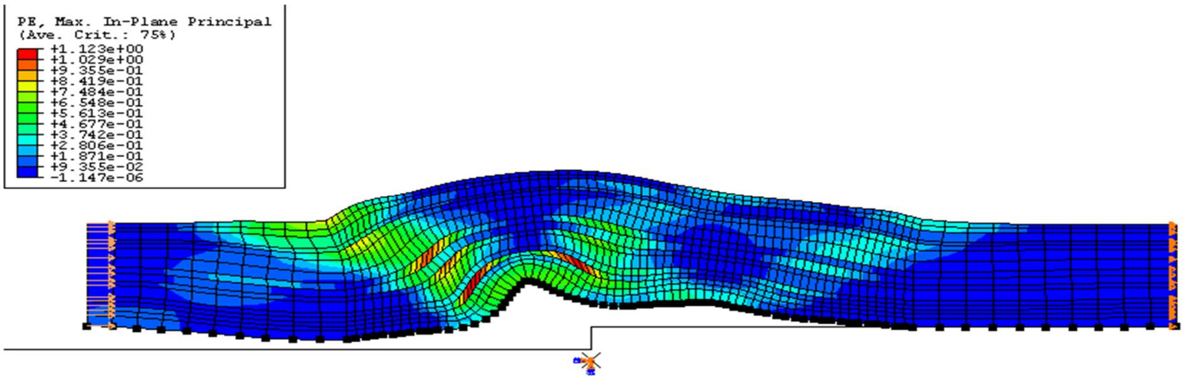

Figure 6- Max in-plane principle plastic strain (case 2)

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