Understanding Mechanics of Fold-Thrust-Belt through Sandbox Modelling

Benyamin Sapiie\textsuperscript{1}, Meli Hadiana\textsuperscript{1}, Terry A. Furqan \textsuperscript{1}

1. Geodynamic Research Group, Institut Teknologi Bandung, Bandung 40132, Indonesia

bsapiie@geodin.net

Abstract. One of major challenge and complex issue in structural geology is understanding the mechanism of Fold-Thrust-Belt (FTB). Numerous authors have been worked to solve these particular subjects in the past. However, most of them are concentrated in describing internal deformation and their tectonic evolution. FTB deformation is very complex due to their natural geological parameters which control their geometries and styles. Although, in natural example often difficult to analyse this parameter using outcrops or seismic reflection data due to the poor image quality as a results of complex deformation styles particularly in the form of tight folds and steep faults. Therefore, in evaluation FTB need to generate special approach which focus in integrating result of palinspastic reconstructions trough balancing cross-sections and sandbox modelling. This paper will present results from series experiment using analogue sandbox modelling for ramification mechanics of FTB and their associated structures. The main focus of the experiment is evaluating main geological parameters in controlling geometry and fault styles of several different tectonic setting. The results of the study show the importance roles of preexisting structures or basement configuration in controlling end results of FTB deformation styles. Others geological parameter such as variation lithology governed by facies and package thickness are considered as mechanical stratigraphy which play key roles in strain distributions. In addition, their initial slope is among the important parameter which clearly influenced in the final results of deformation. Among all, basement configuration is one of the parameters seems to have major impact in fault styles such as thin-skinned versus thick-skinned FTB. Understanding these initial parameters conditions are very important in order to have the best modelling results representing natural examples. The result of this study was validated using 2D seismic data from Eastern Indonesia which consider as the main frontier exploration hydrocarbon in FTB setting.

1. Introduction

Structural geology focuses in rock deformation in the crust that is resulted from the plate tectonic process. Tectonic force continuously presses, pushes, pulls bends and breaks rock in the lithosphere. The energy came from the earth thermal energy that changed into the mechanical energy via convective heat flow. Deformation is a slow process and it is too deep to be observed. However, the deformation products exposed to the earth surface as mountain ranges and basins. In Sumatera Island for example, the interaction between the Indo-Australian and the Eurasian plate has formed a very complex geological region represented by a combination of high, continuous mountain ranges, deep basins and frequent earthquake occurrence. One of the problems in understanding deformation of the Earth’s crust is simulating the development of geological structure. Analogue Sandbox Modelling (ASM) is a method of analogue restoration in geological science which has a goal to simulate style and development of deformation within sedimentary sequences could provide useful insight in solving the problem. Research of rock deformation by utilizing analogue modelling could improve the understanding of structural evolution via in situ observation on rock properties. Comparison between initial (predeformation) and advance stage of deformation can be carried out to analyse the progress of a certain setting of rock deformation.
The study aims to specify the mechanical behaviour, morphological development and internal strain accumulation outcome from deformation from ASM, to determine the distribution characteristics of the structure, pattern and style resulting from various deformations setting from ASM. This knowledge is the cutting edge in studying the global tectonics, geological hazards and exploration of natural resources.

2. Data and Method

Integration study of regional 2D seismic interpretation, surface geological mapping, and palinspastic reconstructions using balancing cross-section technique is the concentration of this study, thus the result will be simulated using analogue sandbox modelling (ASM). Several results of ASM including their sensitivity analysis are also will be explained.

ASM aims at simplifying the examples in nature and are based on the similarity of the symptoms shown by a problem and that is shown by the model. Through this method we can minimize the problems associated with the development of the structure due to deformation of the rock. That is because, this method makes it possible to connect and compare the initial conditions before the rocks deformed by the state thereafter. This comparison is an important part in understanding the development and evolution of structural deformation resulting from the setting of certain rocks, especially in sedimentary basins (Sapiie et al, 2012).

Physical modelling using ASM has been conducted since the beginning of 1940’s, but unfortunately the results does not meet satisfaction to all geological conditions. A factor producing this outcome is the problem in establishing initial boundary condition. Boundary condition determines the initial phase of material types that would be used in the model and limit the material usage during the modelling experiment. It has been demonstrated that similar experiments may yield different results, as example experiments conducted by Eisenstadt and Withjack (1995), and by Ellis and McClay, (1988). However, the good results of the model that visually depicts a condition similar to the geological structure, remains to be analysed critically and carefully (Eisenstadt and Withjack 1995). It is important to compare this with the results obtained from detailed field work from known areas, for better understanding about physical parameters. Experimental studies using analogue modelling now has been used extensively in the field of geological structures. This technique became one of the most effective ways to study the deformation of rocks in laboratories especially sedimentary rocks. Simplifying examples in nature, although information about the nature in situ are very little, could be modelled and studied. In the last twenty years analogue model gave a significant advantage and proved to be a tool that is relatively inexpensive but effective for investigating tectonic processes.

The experimental apparatus was designed for simulating various experiments and deformation of contractual tectonic setting. It includes two walls that one of the wall can be moved by geared motor drive (Figure 1). Analogue material is natural dry quartz sand collected from Ngayong Formation cropping at Tuban area of East Java. This sand has several criterion that suits for conducting ASM such as: (1.) Follows Mohr-Coulomb criterion of failure, (2.) Very low cohesion strength with (3.) angle of
internal friction ($\phi$) determine by shear test of about 30°, similar to many sedimentary rocks in the upper crust (Byerlee, 1978) with (4.) bulk density of 1.5 g/cm$^3$ and (5.) homogenous grain-size distribution with average of $< 0.5$ mm. Modelling parameters were scaled based on their natural examples and the experiment was run using displacement rate of 5 cm/hour (2.2x10^{-4} mm/second). The sand pack is made of thin alternating coloured layers, which allows the identification of faults and folds on cross-sections. In order to ensure the consistency of the results obtained, the experiments were repeated several times.

In this paper, we introduce a method for evaluating deformation process and displacement vector using Particle Image Velocimetry (PIV). This method is in direct and non-intrusive method commonly used in fluid mechanics which allow to identification displacement vector. There are two main principles of method, namely: peak cross-correlation and peak displacement measurement (Figure 2). Before the measurement is taken, the image will be divided into several parts, called the interrogation window. Within this subdivision, the peaks of its gray values is mapped out, and then matched between the subsequent image in the same coordinate of interrogation window, this is the first step. Thus those matched peak distance are measured and we have our displacement value (Raffel et al., 2017). In theory, maximum resolution resulted from this method can reach 0,125 mm/pixel (Wolf et al., 2003) depending on camera resolution used in the modelling (Adrian, 2005). PIV have been used in evaluating displacement vector of granular materials (i.e. Schnatz et al., 2010; Sielamowicz et al., 2006; Steingart and Evans, 2005). PIV usage is pioneered by Adam et al. (2005) and shows very interesting insight in understanding deformation in sandbox modelling.

![Figure 2. PIV method and analysis used in this study for evaluating and calculating displacement vector](image)

In this study we develop the PIV further by measuring the speed of the moving components during deformation. By measuring those blocks, the deformation history of the model can be obtained, example of graph that reflects the movement pattern of the block can be seen in Figure 4. Furthermore, by using this method the history of faults displacement, layer parallel compaction occurrence pattern, and out of sequence thrust occurrence pattern can be obtained.

Continuous research at the Geodynamic Laboratory, Study Program of Geological Engineering ITB, focuses on the development of analogue modelling, especially in the field of geological structures and tectonics. This paper explains the extent of the capability our ASM to reproduce contractional deformation particularly Fold-Thrust-Belt (FTB) which is observed in nature.

3. Result and Discussion

The geological boundary condition as well as deformational setting for generating sandbox modelling are built based upon results of palinspastic reconstructions. Verification, simulation and evaluation of fault evolution of FTB model are the main purpose of ASM. In order to generate appropriate sandbox model the study area is best-modelled using critical taper model where sediments pushed foreland ward by a rigid buttress in the hinterland.
Ten (10) different modelling setting is carried out and investigated to understand deformation of the Eastern Indonesia FTB. Based on seismic reflection data, and thickness as well as geometry of the wedge, we use 4° initial slope (Figure 3). We find out that initial geometry and basement configuration are sensitive to total number of faults produced, fault dip and thickness of the wedge. The total numbers of fault increasing with increasing shortening and back-thrust develops in all different modelling setting. Imbricated thrust system (duplex) are common in deformation influenced by basement. In contrast, inclined model tends to develop higher number of faults rather than flat model. One of the most interesting thing faults in this experiment is, in some cases there is a tendency to decreasing fault dip whilst the shortening are increasing. Although, in general faults evolution shows dynamic changes they are relatively forming simple and constant pattern which are increasing dip until 20%-30% shortening and begin to flatten after 35% shortening. This evidence suggests that within the FTB deformation maturity due to burial can be correlate to the value of shortening which depend of geometrical setting of the sedimentary packages. Result of PIV analysis suggest deformation is concentrated along active fault (Figure 4). This result is very important for evaluating hydrocarbon migration due to FTB deformation.

![Figure 3. Comparison results of ASM in FTB deformation using various different geological boundary setting](image1)

![Figure 4. Comparison results of ASM in FTB deformation using various different geological boundary setting](image2)

Based upon evidence in the Eastern Indonesia including Seram, Tanimbar and Timor FTB, inclined model will result in higher maturity compared to horizontal setting. In order to explain the present of oil in thrust wedges, deformation must be formed very young after oil maturity were reached. It suggests that oil migration is coincide with thrusting mechanism. Otherwise, very different source rock characteristic is needed to explain these phenomena, which rise to the question of paleogeography of the region. More work need to be done to ramification this issue.

4. Conclusion
The best method in order to evaluate structural complex area such FTB is integrated structural analysis using ASM and 3D palinspastic reconstructions with several remarks of the study are as follow:
1. The thickness of the sedimentary package, initial geometry and basement configuration are the major factor of structural development in the FTB.
2. The width of deformation zone in FTB controls the taper angle of the sedimentary wedge.
3. Rather than thickness of the model, the geometry are more sensitive / prone to produce different faults pattern.
4. pre-existing basement configuration are the main factor in controlling deformation in the FTB, based upon the results of ASM experiments, resulted in asymmetry strain distributions.
5. PIV analysis is very useful for evaluating deformation behaviour as well as possible fluid migrations.

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