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Modeling principal plate tectonic processes by sandbox experiments: Tools for teaching at universities

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KEYWORDS

Sandbox experiment
Plate tectonics
Normal fault
Thrust
Teaching

ABSTRACT

Analogue sand models have been used to reproduce the principle plate tectonic processes, providing the insight of plate tectonics in nature. A simple and versatile sandbox was built and used for the extension and compression experiments modelling principle plate tectonic such as plate divergence or convergence by stretching or compressing sand in a sandbox model. The glass sidewalls allow observing and analyzing the sequential development of faults and structures like normal fault, thrust fault, graben structure, fold and thrust belts, so on. The results can be correlated with geological structures in nature. In an educational context, students can perform the experiments and also vary experimental parameters such as sand layer thickness, geometry of the sandbody or use of different experimental materials. The obtained results are then compared with natural geological examples to improve the students' receptivity. This indicates that sandbox experiments provide an effective means for teaching geology courses and also soil mechanics courses at universities.

1. Introduction

Plate tectonics is a scientific theory that has been used in the past decades. It provides a complete reference system on the formation and development of geological structures, the distribution of continents and oceans. The theory, especially, provides the insight of geological phenomena, including mountain building events, seafloor spreading, earthquakes, volcanic island chains' distribution, etc. [1]. In plate tectonics, Earth's outer shell, or lithosphere – including the crust and upper mantle, is broken into large rocky plates. These plates move relatively to each other on top of a partially molten layer of rock at different rates, from two to 15 centimeters per year [2]. According to the movement of the plates, three principal types of tectonic boundaries can be defined: boundaries of divergence, where plates move apart and usually forming mid-ocean ridge; boundaries of convergence, where plate moves into one another; and transform faults, where plate moves sideways in relation to each other [3].

Analogue sand models have been widely used in the study of geological structures. Analogue materials were used for simulating behaviors of real rock and soils such as sand and clay as brittle behavior and wax, honey, beans and other materials for simulating ductile/plastic behavior [4, 5]. Horsfield (1977) showed that dry sand could be used to simulate the rheological properties of moderately cohesive sediments with a scale factor of between 1:10 000 and 1:100 000. Dry sand has an angle of internal friction of $\varphi = 30 – 32\,^{0}$, which is similar to that determined for brittle sedimentary rocks in the upper continental crust. In addition, dry sand has such very low cohesive strength, that allows millions of years of tectonic deformation in sedimentary rocks to be performed in hours or even less in sandbox experiments [6].

Sandbox experiments provide an effective means of simulating tectonic processes such as convergence or divergence of plates by compressing or stretching sand in sandbox model. One of sandbox apparatus known as a great successful analogue modeling was proposed by F.K.Lehner in the 1970s. This sandbox apparatus has been used by many scientific groups [7-9]. The deformation process and resulting structures observed in sandbox modeling not only provide further insight into tectonic activities, but also help to interpret the nature of the associated mechanism. Lu and Malavieille (1994) performed 3-D sandbox modeling experiments to manifest the evolution of the Taiwan thrust wedge during oblique convergence with different tectonic mechanisms involving compression, rotation and extension, resulting in a local separation between thrusting and strike-slip faulting [10].

Currently, sandbox experiments combined with numerical simulations help scientists access and deepen their knowledge of complex geological structures [11-12]. On the other hand, sandbox modeling has been applied for educational purposes in many universities in the world. A pilot study using the sandbox suggests it can be an efficient tool for introductory geology students. Students are provided geological contexts and allowed to perform the experiments by themselves. This engagement helps students understand the principal or complex tectonic processes as well as improve the learning interest [4, 13]. In this paper, we present the sandbox apparatus designed for use in teaching construction engineering students at the university of Technology and Education, the university of Danang, Vietnam. We also present the experiments modeling the principal plate tectonic processes as well as the associated explanation.

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2. Sandbox and experimental setup

2.1. Sandbox apparatus:

Sandbox apparatus used in teaching can be built simply and needs no expensive materials, these are important requirements for universities. The sandbox has a rectangular shape with inside dimensions of 70 cm in length, 20 cm in width, 20 cm in height, which is adaptable for classes of about 20 students. These dimensions can be adjusted depending on classroom area and number of students. The sides of the sandbox, including sidewalls and basal plate, are all made of glass with a thickness of 0.5 cm and fixed in position, allowing to observe the deformational processes throughout the tests. Since the glass material has a smooth surface, it can reduce the friction induced by the lateral boundaries. The basal plate of the model has a slope of 0 °. Two foam blocks are placed perpendicularly with the base of the sandbox at the two ends of the box, allowing compression tests from both sides (Figure 1). Two gauges detailed in millimeter are mounted horizontally at the bottom of the box and vertically at the back of the wall, respectively, to measure the horizontal displacement of the material and the accreting height of sand wedge during the tests (Figure 2).

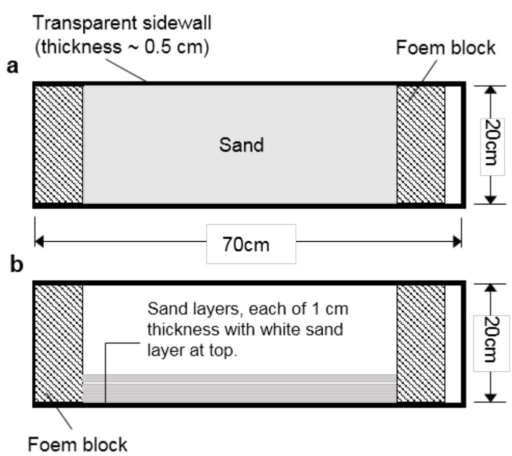

Figure 1. Schematic setup of sandbox apparatus: a. Plan view of sandbox; b. Side view of sandbox – flat base model.

Figure 2 shows a practical sandbox model used in teaching at university of Technology and Education, the university of Danang. It's quite simply built but very flexible and effective.

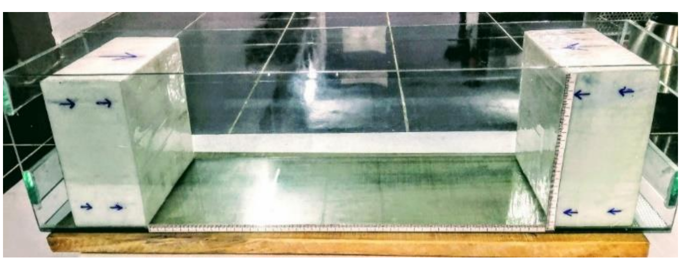

Figure 2. Sandbox apparatus used in teaching at university of Technology and Education – The university of Danang.

2.2. Experimental materials:

The granular material tested is clean, dry, cohesionless sand, consisting of two types - yellow sand and white sand. The sand tested has a median grain size of about 0.5 mm, and is composed primarily of quartz containing also a minor portion of feldspar and mica. These types of sand are common materials and easy to obtain in construction trade-shops.

The yellow sand deposited into layers represents the sedimentary layers and its internal layer is highlighted with white sand. The use of sand with different colors allows one to observe deformational processes in side view. The total height of sand layers is about 3 cm. Two experimental groups including compression tests simulating the convergence of plates and extension tests simulating the divergence of plates will be presented in the next section.

2.3. Experimental setup

The experiments consist in shortening (compression test) and stretching (extension test) lengthwise a uniform sand body of flat layers. In compression tests, compressive force was created by pushing the foam block versus the sand body. Sand layers were shortened and gradually formed faults (Figure3a). In compression tests with high frictional base, a sandpaper was put entirely on the bottom plate to increase the basal friction and then overlain by sand layers as mentioned above.

The Figure 3b illustrates the setup of extension tests. The sandpaper was put partially on the bottom plate and divided the base of sandbody into a "fixed" area and a movable one. To make the sandbody stretch, one can simply pull the sandpaper.

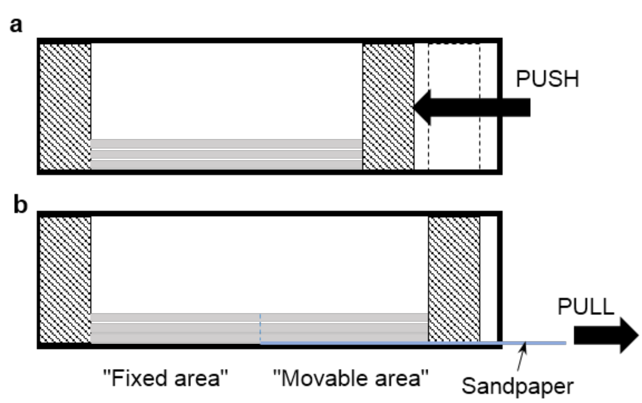

Figure 3. Experimental set-up: a. Compression tests, b. Extension tests

Several experiments could be performed with each set-up to demonstrate the reproducibility of the results that will be presented in the next section.

3. Results and discussion

3.1. *Reverse fault/thrust and fold-thrust belts:*

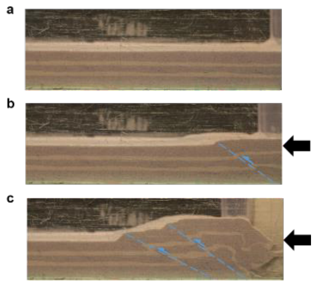

Figure 4. Deformation patterns obtained in compression tests: a. Initial state, b. Formation of the first thrust, c. Formation of the next thrust.

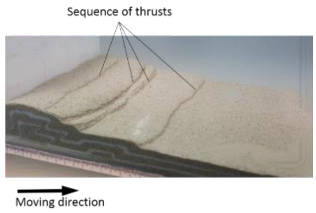

Figure 5. Sequence of thrusts at the end of the test showing the typical thrust curvatures (oblique view of sandbox). The arrow indicates direction of convergence.

As mentioned in the section above, the compression tests were conducted by pushing the foam block versus the sandbody, resulting in bulk lateral shortening and thickening of the sandcake. The compressive force initially made the sandbody compressed and deformed. The deformation of sand was then localised into a thrust (Figure 4b). The contractional process continues leading to the formation of other thrust faults. One can see clearly a series of fold and thrust belts forming in the forelands at the end of shortening. This could be explained as the total shortening increased in a fold and thrust belt, the belt propagated into its foreland. New thrusts developed at the front of the belt while the older thrusts became inactive and were folded (Figure 4c, Figure 5).

In nature, fold and thrust belts are found on the continental or foreland margins (e.g. the Pyrenees [14]; the Canadian Rocky Mountains [15]; Jura Mountains [16]). The thrust belts characteristically consist of platform sediments deformed by thrust faults which have a ramp-flat trajectories. Steps in the thrust surface generate geometrically necessary folds in the hanging wall above [17-18]. In general, thrust faults, thrust systems and related structures are complex and still rest many challenges for geologists. The sandbox model is designed herein to focus on brittle deformation of the upper crust and used for ideal compression experiments concerning the thrust fault, the sequential activation of thrust faults and the overall geometry of thrust belts.

3.2. *Normal fault, graben structure and rifts:*

In the extension test, after pulling the sandpaper beneath the movable zone a few millimeters, a normal fault existed and then a trench structure, known as graben, was formed (Figure 6b, Figure 7). This structure was characterized by a narrow band bordered by parallel faults that widened and deepened as the mobile zone continued to move apart. As in nature, this is the result of crustal stretching, splitting to form valleys or ocean basins.

A rift is a place where the Earth's crust and lithosphere are being pulled apart and fractured into a series of normal faults forming the classic horst and graben structure. The stretching process associated with rift formation is often preceded by huge volcanic eruptions. A few prominent examples of rift structures are East African Rift system [19]; Lake Baikal – the deepest continental rift on the Earth; the Rio Grande Rift in the Southwestern US [20]; the Oslo graben in Norway [21] and the Rhine graben in Germany and France [22].

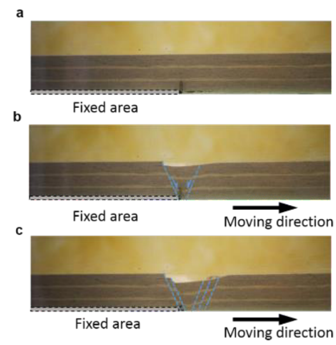

Figure 6. Deformation patterns obtained in extension tests: a. Initial state, b. Formation of a single graben, c. Widening and deepening process of graben structure.

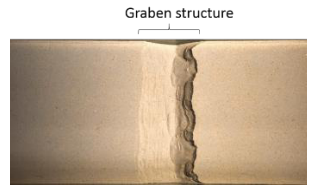

Figure 7. Graben structure obtained at the end of the test (plan view of sandbox).

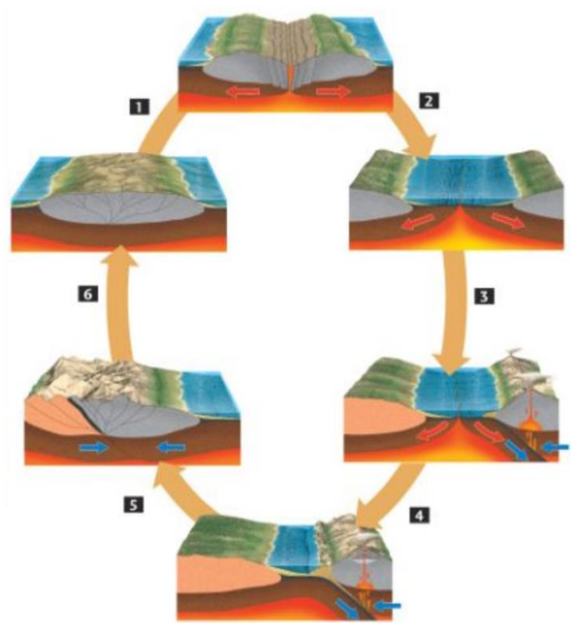

Figure 8. Stages of the Wilson cycle: 1. Embryonic Ocean Basin, 2. Juvenile Ocean Basin, 3. Mature Ocean Basin, 4. Declining ocean basin, 5. Terminal Ocean Basin, 6. Continental Collision [27].

The sandbox experimental results can illustrate the formation processes of principal tectonics like reverse faults with fold structure, normal fault with rifts and graben structures. These are parts of different stages in plate tectonic cycle, also known as the Wilson cycle, named after the Canadian geophysicist J.Tuzo Wilson. The Wilson cycle explains the process of the opening (beginning) and the closing (end) of an ocean basin (Figure 8). Over five decades have passed since Tuzo Wilson first proposed the concept of the Wilon cycle in 1986 [23]. Currently, the Wilson cycle has proved enormously important to the theory and practice of geology and is fundamental to the theory of plate tectonics that helps us know more about the geological evolution of the Earth [24-27].

4. Conclusions

In the geosciences, analogue sandbox models have been proved to be an effective tool for studying geological structures and their processes in nature. A simple sandbox apparatus is simple built and not expensive, allowing to carry out the principal plate tectonics such as the convergence and divergence of plates by compression and extension tests, respectively. The transparent glass of sandbox sidewalls authorizes to easily observe and analyse the deformation process, the formation of faults and related structures such as normal fault, graben structure, thrust, fold-thrust belts and so on. In an educational context, students may be asked to perform various experiments to answer the posed subjects. In addition, students can vary experimental parameters such as sand layer thickness, geometry of the sandbody or use of different experimental materials, thereby comparing the obtained results with natural geological examples for improving the visualization of lectures as well as students' receptivity.

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