Analogue and numerical modelling of accretionary prisms with a décollement in sediments

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Abstract: Active accretionary prisms at subduction margins generally include a horizontal detachment, décollement, within the sedimentary pile. The décollement, and its extension to undeformed regions (i.e., proto-décollement), corresponds to a layer of high fluid pressure. The deformation of the prisms, including such an anomalous layer, can be modelled and examined using analogue experiments and numerical simulations. Both these methods approximate the material under deformation as an assembly of particles (grains). The décollement layer is found to be best modelled by intercalating a layer with smaller internal frictional coefficient than the surrounding materials corresponding to the sediments. Our analogue experiments with dry sand and microglass beads reproduce structural geometry similar to that of interpreted seismic profiles at the toe of the prisms. Thrust faults originate from the horizontal beads layer and propagate upward with a constant angle of about 30°. Each of the fault bends produces a series of minor back thrusts. A particle image velocimetry (PIV) analysis revealed that the fault activity is characterized by intermittent reactivation and segmentation. The numerical simulations based on the distinct element method (DEM) were performed with similar kinematic settings and material properties as the analogue experiments. The numerical simulation results not only reproduce similar geometries as in the analogue experiments, but also show that the particle assembly experiences temporal variations in the deformation velocity and stress field as deformation propagates. This might be related to stick-slip motion of the frictional fault surfaces, which is a common feature of faulting during accretionary processes at subduction margins.

Geological modelling using physical materials in scaled analogue experiments is an extremely useful technique for a detailed examination of the geometry and deformation process of accretionary prisms. Since the mechanics of the upper crust can be approximated by Navier-Coulomb brittle behaviour, granular materials such as dry sand are an appropriate material to model such brittle deformation (McClay 1990) with fulfillment of the scaling theory by Hubbert (1937). Analogue experiments with dry sand (sandbox experiments) have thus been widely applied to simulate a wide variety of geological structures (e.g., Mandl 1988; Cobbold & Castro 1999; Koyi & Mancktelow 2001; Yamada & McClay 2003a, 2003b, 2004; Yamada et al. 2005 and the references therein). Accretionary prism formation, as well as thrust-and-fold belts, has been investigated in detail by a number of analogue models (e.g., Colletta et al. 1991; Huiqi et al. 1992; Willet 1992; Lallemand et al. 1992; Mulugata & Koyi 1992; Gutscher et al. 1996; Nieuwland et al. 2000; Koyi & Vendeville 2003).

There are two types of model kinematics, either pushing a rigid backstop or pulling a sheet underneath sand, but the results are the same except for the boundary effects of side-walls (see Schreurs et al. 2006). A typical result of these models shows that a foreland propagating (piggyback) sequence of thrusts form a Coulomb wedge with a taper mainly dependent upon the friction of the detachment fault. That is, higher basal friction leads to formation of a steeper slope prism, whereas low basal friction leads to formation of a gentler slope prism. This corresponds with the basic theory of non-cohesive critical Coulomb wedges (Davis et al. 1983; Dahlen 1984; Dahlen & Suppe 1984), assuming that an actively accreting wedge attains a critical taper, an internal state of stress on the verge of Coulomb failure throughout. Dahlen (1984) concluded that the surface slope of a critical taper is dependent on the internal and basal friction coefficients, internal and basal fluid pressure ratios, the dip of the basal detachment and the strength of the rock composing the wedge. The theory explains how basal


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friction or basal fluid pressure controls the structural styles, including subduction erosion, active accretion, subduction without accretion and normal faulting (Dahlen 1984).

Deformation of granular assemblies can also be simulated numerically using the distinct element method (DEM). The DEM calculates force and velocity in two (normal and shear) directions for all elements, which is repeated for the updated element relations at the next time increment (Cundall & Strack 1979). With significant advances in computing technology, the technique can now handle a large number of elements and be applied to a variety of research fields (e.g., Konietzky 2002; Shimizu et al. 2004). Application of the DEM to geological problems requires the geological body to be approximated as an assembly of elements (e.g., Finch et al. 2003); thus sandbox experiments are an ideal scenario (e.g., Saltzer 1993; Yamada et al. 2004). Numerical models using the DEM are, however, not scale models in the sense of physical models where typical Earth values are used as their input parameters (Strayer & Suppe 2002). Two significant advantages of the DEM are: (1) no need to predefine artificial parameters of discontinuity surfaces, and (2) ability to extract all information from each element during deformation in a quantitative way. The DEM therefore has high potential to be a numerical simulator that can incorporate discontinuity surfaces properly.

This paper shows selected sandbox experiments and DEM simulations for a simplified geological model of accretionary prisms. The results are analysed to investigate the detailed process of fault development.

Accretionary prisms with a décollement in sediments

Recent investigations revealed that the accretion process at subduction margins generally develops a sub-horizontal detachment, décollement, within the sedimentary sequences accumulated in the trench area. This horizon is typically defined by a layer of anomalous high fluid pressure and can generally be easily traced with reverse polarity on seismic profiles (Tobin et al. 1994; DiLeonardo et al. 2002; Tsuji et al. 2004; Bangs et al. 2004). The sediments above the décollement are deformed by a series of imbricate thrusts that converge with the décollement surface, whereas those underneath it are subducted without internal deformation.

A typical example can be seen in the Nankai trough located offshore southwest Japan, where the Philippine Sea Plate is subducting underneath the Eurasian Plate at a rate of 4 cm/yr along an azimuth of 310°–315° (Fig. 1; Seno et al. 1993). Extensive seismic surveys in this area reveal that a décollement is clearly located within the sediments, not at the top horizon of the volcanic basement (Fig. 2a; Bangs et al. 2004). The reverse polarity of the décollement suggests that the layer may have extremely high fluid pressure, even at the ‘proto-décollement’ region (Tsuji et al. 2005). The proto-décollement is an extension of the décollement surface in the undeformed sediments, seaward of the deformation front. This clear identification of the proto-décollement on the profiles suggests that a preferred layer of décollement exists prior to initiation of the actual displacement. Geophysical logging and core analysis at Site 1174 of the Ocean Drilling Project Leg 196 showed that the décollement is located in a hemipelagic mudstone sequence at Nankai (Mikada et al. 2002).

Such features of décollement development are also observed in Barbados (DiLeonardo et al. 2002) and in Cascadia (Tobin et al. 1994). The décollement in the Barbados accretionary prism, where the Atlantic Plate is subducting underneath the Caribbean Plate, is located in a radiolarian mudstone of high porosity and low strength (Moore & Klaus 2000). This horizon also forms the proto-décollement. In Cascadia, a large scale accretionary prism develops due to the subduction of the Juan de Fuca Plate underneath the North American Plate, and the décollement (and its proto-décollement) is formed at a boundary horizon between upper turbidites and lower hemi-pelagic mudstones (Westbrook et al. 1994). The structural styles

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**Fig. 1.** Location map of the Nankai Trough and the section line.
of these prisms are generally similar on seismic profiles.

The experiments and simulations aim to investigate the effects of the décollement within the sediments. Figure 2b is a seismic profile illustrating the characteristic structural style at the toe of the Nankai prism off Muroto Point. The thickness of the sediments above the décollement is c. 800 m, fault spacing at the toe is c. 1300 m, and the slope angle is c. 4°.

**Analogue experiments**

**Modelling set-up**

The experimental apparatus is an acrylic box (25 cm × 150 cm × 50 cm) underlain by a flat plastic sheet (Fig. 3). Layers of analogue material are piled on the sheet, which is then pulled by a motor at a constant speed of 1.67 × 10^{-2} cm sec^{-1} through a slit under the fixed end wall. This slit produces a décollement horizon within the analogue material. The scaling ratio is 4.0 × 10^{-3}, thus 1 cm in the experiments corresponds to 250 m in nature.

Selection of the modelling materials is an important factor of the analogue experiments. In this study, the effects of the anomalous high fluid pressure along the natural décollement must be considered. The high fluid pressure reduces strength, both in nature and in experiments. Low friction materials thus may be used to approximate the effects of the fluid pressure. In fact, a pioneering work by Cobbold et al. (2001) showed that an increase in the inter-granular pore pressure of a layer in their thrust-wedge-type sandbox experiments produced a decreased taper angle and widened fault spacing. These effects are similar to the experiments with a décollement of a smaller internal friction coefficient. Microbeads have been recently regarded as suitable materials for such weaker layers (e.g., Massoli et al. 2002; Lohrmann et al. 2003; Yamada et al. 2005). We used Toyoura dry quartz beach sand and glass microbeads as analogue materials. The average grain sizes are 200 μm and 50 μm respectively. Our shearing tests showed that the microbeads have a much smaller internal friction angle (25°) than Toyoura sand (34°, see Table 1).
This paper presents two representative results of sandbox experiments conducted for this study. Experiment I employs pure sand of 6.0 cm thickness, whereas Experiment II includes a layer of microbeads (0.4 cm thickness) midway up the sand pile (6.0 cm in total including the beads layer). The microbeads are white and the sand is naturally light brown, thus they can be easily distinguished. We also used dyed marker sand layers only adjacent to the transparent sidewalls. The marker sands have almost the same physical properties as the undyed sand. These are to maintain the homogeneity of the sand layers. During the experiments, photographs were taken through the sidewall after every 1 cm of displacement of the sheet.

The structural style on the free surface suggests that the deformation of the experiments can be approximated as plane strain.

**Experimental results**

**Experiment I.** The homogeneous dry sand model reproduced typical thrust-and-fold belt structures including a wedge geometry, and foreland vergent thrusts that propagated upward with a piggyback sequence from a sub-horizontal décollement produced within the sand pack (Fig. 4). The décollement connected to the frontal thrust without forming a bend. The angle of the prism surface (line linking the tips of the thrusts) is $c. 18^\circ$ to $24^\circ$ and fault spacing near the frontal thrust is $c. 6.0$ cm (corresponds to 1.5 km).

**Experiment II.** The results of this model, which has a microbeads layer inserted into the sand, showed that the microbeads layer acted perfectly as a horizontal décollement (Fig. 5). Detailed observations revealed that the décollement surface was at the lower boundary of the microbeads layer. The analogue material below the décollement did not deform and was expelled from the experimental rig through the slit. From the décollement, the foreland vergent frontal thrust propagated upward, dipping $c. 28^\circ$ to $34^\circ$. Thus, the active surface of the frontal thrust through the décollement has a bend where the frontal thrust is generated from the décollement. Above the bend, a series of minor back-thrusts was generated in a piggyback sequence, which was only active while the fault underneath was active. The foreland vergent thrusts also formed a piggyback sequence. In Experiment II, the angle of the prism surface (the slope of the line linking the tips of the thrusts) is gentler ($c. 9^\circ$ to $14^\circ$), and the fault spacing near the frontal thrust is wider ($c. 8.3$ cm, corresponding to 2.1 km), than in Experiment I (cf. Fig. 4).

**PIV analysis**

In order to analyse the deformation process in detail, time-lapse digital pictures of the

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**Table 1.** Material properties and grain characteristics of analogue materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density ($\text{kg m}^{-3}$)</th>
<th>C (Pa)</th>
<th>$\phi_{\text{stable}}$ (°)</th>
<th>Strain soft. (%)</th>
<th>Ave. grain size ($\mu$m)</th>
<th>Grain shape</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz sand</td>
<td>1390</td>
<td>n.d.</td>
<td>34</td>
<td>9</td>
<td>$m = 200$</td>
<td>Angular</td>
<td>93% SiO$_2$ 4% Al$_2$O$_3$</td>
</tr>
<tr>
<td>Microbeads</td>
<td>1420</td>
<td>n.d.</td>
<td>25</td>
<td>0</td>
<td>$m = 50$</td>
<td>Spherical</td>
<td>Na$_2$O–CaO–SiO$_2$</td>
</tr>
</tbody>
</table>
experiments were evaluated with an image correlation technique called particle image velocimetry (PIV). This technique is commonly used for dynamic flow analysis and soil mechanics (e.g., Hryciw et al. 1997), but has recently also been applied to structural geology (Adam et al. 2002; Wolf et al. 2003; Adam et al. 2005). The method calculates the displacement field of the grains with a theoretical resolution of \( c.0.5 \) mm. The displacement accuracy depends on the picture size and the resolution of the digital camera (Wolf et al. 2003). PIV data cover the complete range of structural evolution, as well as a major part of the stick-slip field, in experiments with a scaling factor of \( 10^5 \) – \( 10^6 \) (Adam et al. 2005).

Figure 6a is an example of the photographs that have been taken after every 1 cm of displacement of the plastic sheet and that have been analyzed using PIV. The results are shown in Figure 6b, in which the fixed wall and the basal plate provide axes of a frame of reference for the kinematics of the model. Dark arrows correspond to large displacement, whereas light grey arrows correspond to minor displacement. White areas with no arrows correspond to regions where the software detects no correlation. These displacement distributions identify coherent blocks of active displacement, the discontinuities between such blocks indicating active faulting. The top diagram is the displacement distribution between the images taken after 38 and 39 cm of total displacement, showing that the hanging wall of the frontal thrust is moving to the upper-left relative to the fixed wall, whereas the rest of the regions only show minor displacement in other directions. This suggests that shortening is mainly accommodated by the frontal thrust. The displacement distribution between 39 and 40 cm of total displacement shows a similar pattern to the previous stage described above. However, minor differences can be found in regions of previous thrust sheets, suggesting that these thrusts are reactivated.

The displacement pattern then changes significantly after 40 cm of total displacement. According to the PIV calculations, the frontal area shows a similar displacement distribution between 40 and 42 cm of total displacement as between 39 and 40 cm displacement, but the adjacent area has a large displacement anomaly that drops sharply along the third thrust fault from the frontal thrust. This means that the third thrust fault reactivates between 40 and 42 cm of total displacement. The hanging wall of the thrust fault also shows such a discontinuity in displacement distribution, suggesting that a back thrust also reactivates at this stage. These thrust faults are inactive during the stages from 38 to 40 cm of total displacement.

The PIV results generally confirm the in-sequence thrust process, but each thrust sheet has an intermittent displacement distribution. Adam et al. (2005) also reported such temporal activity of faults, characterized by fault reactivation, in their thrust-and-fold type experiments.

Numerical simulations

The distinct element method (DEM) was employed as the numerical simulation technique in this study. The model domain consists of discrete circular elements, and linear elasticity (force-displacement law; Cundall & Strack 1979) is incorporated through normal and shear forces at elemental contacts. The inter-element friction in the shear direction is determined by the normal force and a friction coefficient. The size of each element is preserved during deformation, thus volume change (i.e., dilation) is
Fig. 5. Results of Experiment II (the length values are amounts of shortening). A layer of microbeads inserted into the sand pile acts as a horizontal décollement. Only the analogue material above this layer is shortened (see Fig. 3a). Thrusts propagate upward from the décollement, forming a piggyback sequence. Note that each thrust has a bend where a backthrust is initiated in its hanging wall. The surface slope of the wedge is about 12° at 65 cm of shortening.
Fig. 6. Particle image velocimetry (PIV) analysis for analogue model II. (a) The images analysed are taken at every 1 cm of shortening (the length values are amounts of shortening). (b) The results of PIV analysis showing the velocity vectors during shortening. The fixed wall and the basal plate provide axes of a frame of reference for the kinematics of the model. Dark arrows correspond to large displacement, whereas light grey arrows correspond to minor displacement. White areas with no arrow correspond to a region where the software detects no correlation. Note that the velocity patterns suggest sequential fault reactivations.
Fig. 6. Continued.
accommodated by the inter-element porosity. The method has two steps in each calculation cycle (time-step): the first step is to evaluate interaction forces for every element, and the second step is to move all elements according to numerical integration following Newton’s equation of motion for the given external forces. The software employed in this study is PFC 2D developed by the ITASCA Corporation, Minneapolis, USA.

Input parameters

The simulations aim to reproduce the two-dimensional structural style of the accretionary prism with a décollement in the sedimentary sequence. In order to make the initial conditions of the simulations similar to those of the analogue experiments, the input parameters are carefully determined after a series of compression test simulations. Since DEM describes only the parameters related to element contacts, such compression tests are necessary to measure the physical properties of the element assembly. Table 2 shows the physical characteristics of two particle types, which were obtained by bi-axial compression tests with a PFC-2D function called FISH-TANK. Particle A has an internal frictional angle of $35^\circ$, while particle B has an internal frictional angle of $25^\circ$. These particle types are selected to model the sand and the microbeads respectively in the analogue experiments (cf. Table 1). The friction coefficient between the wall and the particles is the same as that of particle A. Initial cohesion and bonding between elements are not introduced, due to the cohesionless nature of the analogue materials. The diameter of the elements has a variety of 20% from the average size to avoid formation of preferential weak planes in the initial arrangement of the element assembly.

The model kinematics is also designed after the sandbox experiments, but the polarity of shortening is opposite (Fig. 3b). In this two-dimensional simulation model, an assembly with a rectangular initial geometry is placed on a fixed base, and a horizontally moving wall pushes one side of the material from the left-hand side. The initial position of the moving wall is determined by the position of the décollement horizon. The displacement rate should be small enough to approximate the deformation as quasi-static. In this study, the rate is 0.9 cm for each calculation cycle. This is why DEM requires a few million time-steps to generate sandbox-type deformations.

The sizes of the elements in this study are larger than the equivalent material sizes of the analogue experiments. The use of the equivalent grain sizes requires the computer to be equipped with an extraordinary size of data storage and memory, and each calculation may also require an extremely long time (about a few months with a current workstation). This is why larger elements were generally used in previous research (e.g., Saltzer 1992; Finch et al. 2003; Strayer & Suppe 2002; Yamada et al. 2004). In this paper, two representative results of simulations are presented. Simulation I employs a layer of particle A of 670 m thickness without predefined décollement, whereas Simulation II has a layer of particle B (130 m thick) at the middle of a pile of particle A (1000 m in total including the particle B layer). These thicknesses have to be altered from the equivalent values of the analogue experiments, in order to obtain each calculation result within a month.

Simulation results

Simulation I. The overall structural style is a wedge shape that increases in size as the displacement of the wall proceeds (Fig. 7). The simulation reproduces typical foreland vergent thrusts that propagate upward with a piggyback sequence from the basal décollement. The angle of the prism surface (line linking the tips of the thrusts) generally shows a gradual increase toward the deformation front. This value increases up to $c. 48^\circ$ adjacent to the frontal thrust after shortening of 6750 m (Fig. 7). The fault spacing around the frontal thrust is $c. 0.7$ km.

### Table 2. Material properties and element characteristics of numerical simulations

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m$^{-3}$)</th>
<th>C (Pa)</th>
<th>$\phi_{\text{stable}}$ (°)</th>
<th>Strain soft. (%)</th>
<th>Ave. grain size (m)</th>
<th>Grain shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle A</td>
<td>1600</td>
<td>n.d.</td>
<td>35</td>
<td>n.d.</td>
<td>m = 21</td>
<td>Circular</td>
</tr>
<tr>
<td>Particle B</td>
<td>1600</td>
<td>n.d.</td>
<td>25</td>
<td>n.d.</td>
<td>m = 8</td>
<td>Circular</td>
</tr>
</tbody>
</table>
**Simulation II.** The overall structural style is similar to Simulation I, but the surface slope of the wedge is 21°–22° and the fault spacing around the frontal thrust is c. 1.0–1.2 km (Fig. 8). Similar to the sandbox experiment II, these thrusts propagate upward from the décollement layer; thus the frontal thrust surface has a bend where the thrust originates from the décollement. Although backthrusts were also generated at the bend in the analogue experiments, they are unclear in the numerical simulations. Since the DEM calculates velocity and interaction forces of every element for every time-step, these can be extracted to examine the temporal variability of prism evolution. Snapshots of velocity distribution and interaction force, referenced to the fixed base, are shown in Figures 8b and 8c respectively. On the velocity distribution diagrams, a particle group with a same velocity vector behaves as a block and the boundaries of such coherent blocks are the faults. The velocity diagram thus shows the temporal variation of the faulting. For example, the frontal thrust at the 2250 m shortening stage shows a minor displacement rate in the deeper part of the prism with the rate greater in the shallower part, suggesting an interaction of the second thrust from the deformation front. The deeper part of this second thrust is active at the 4500 m shortening stage, but the entire fault surface of this thrust becomes inactive by 6750 m shortening. The deeper part of the frontal thrust at 4500 m shortening becomes active at 6750 m shortening, but the shallower part is inactive. At the 6750 m shortening stage, the frontal thrust is active only at the tip.

In the interaction force diagrams (Fig. 8c), the black lines are directions of maximum gross contact forces, indicating where, how much and in which direction the forces exist in the assembly. The forces initiated from the moving wall that pushes the elements, and can be traced downward to the base (down-to-the-right direction). Immediately above and underneath the décollement layer, the directions of the forces are generally sub-horizontal. This suggests that the layer with low internal friction coefficient acted as a décollement and affected the pattern of the interaction forces. Within the wedge, the interaction forces also show up-to-the-right directions, which may also correspond to the thrust fault activities.
Discussion
Effects of décollement and implications for accretionary prisms

In both of the analogue experiments and numerical simulations, inserting the décollement, the layer of a lower frictional coefficient, reduces the slope angle (c. 18°–10° in analogue and 45°–23° in numerical; Fig. 9) and increases the fault spacing (c. 1.5–2.1 km in analogue and 0.7–1.1 km in numerical). This is in good agreement with the critical taper theory (Davis et al. 1983) arguing that the internal frictional coefficient along the décollement has a strong impact on the prism geometry. The internal friction angles of two materials (sand/particle A and microbeads/particle B) are almost the same in the analogue and numerical models. The resultant prism geometries are, however, significantly different. This is possibly caused by the smaller number of particles in the numerical simulations. Theoretically, the thickness of the décollement layer consists of 80 (or more) particles in the analogue models, whereas 16 (or more) are counted in the numerical models. This smaller number of numerical particles could not be enough to maintain the physical property of the layer, and the surrounding particle A could increase the internal friction of the décollement layer.
The effects of the low frictional layer in accretionary wedges can be identified in the prism geometry, the detachment geometry and the geometry of the frontal and backthrusts. The slope angle of the Nankai prism is \( \approx 4^\circ \) around the deformation front where the low friction detachment develops within the sediments, and is increased to \( \approx 8^\circ \) where the décollement is inactive. This may be a clear example showing the relationship between the slope angle and the frictional coefficient of the detachment. The detachment surfaces in the Nankai, Barbados and Cascadia wedges are characteristically flat (Bangs et al. 2004; Moore & Klaus 2000; Westbrook et al. 1994), similar to the experimental results. This suggests that the décollement geometry around the frontal thrust is strongly controlled by the pre-existing layers that have an anomalously low frictional coefficient. In experiment II, the active surface of the frontal thrust has a bend where the frontal thrust originates from the detachment. The bend produces a kink zone between the flat and the ramp, and compensation faults should be generated in the hanging wall that moves across the kink zone. These faults are observed as backthrusts. In Nankai, the detachment layer also generates a bend in the frontal thrust geometry and backthrusts in the overlying sediments (cf. Fig. 2b).

**Faulting and stresses**

The analogue and numerical models show variations in the slope angle during prism formation. Nieuwland et al. (2000) describe the dynamic equilibrium that is common to the development of critical tapers, the mechanical necessity of out-of-sequence thrusting and the systematically changing angle of a growing critical taper. That is, a new thrust fault lifts up the front of the taper, thereby reducing the angle, then existing thrust faults become reactivated to restore the critical angle. Our observed variations may be produced by a similar effect, and the process of the prism formation would be strongly controlled by sequential fault reactivations.

The directions of the maximum interaction force (Fig. 8a) presumably indicate the direction of the maximum principal stress, \( \sigma_1 \). This direction theoretically makes an angle of 27.5° with the direction of the active shear zone. Figure 10 shows an interpretation of such shear zone directions, based on the calculated stress orientations. It is predicted that the active shear zones would be steepened upward from the décollement and from the moving backstop. The velocity distributions (Fig. 8b) generally show similar directions, thus this prediction may be appropriate. The prediction also suggests that there may be normal faulting under the décollement. The stress measurements at Nankai accord with this extensional stress regime under the décollement (Mikada et al. 2002).

**Temporal variations due to stick-slip behaviour of frictional faulting**

In the numerical results, the velocity and stress distributions show temporal variations during deformation. These distributions are calculated for 0.9 cm of displacement of the moving wall, thus they are regarded as instantaneous values. These variations should be closely related to the deformation behaviour of the particle assembly. Since no breakage of particles is observed during deformation, the shortening should be accommodated by a change of the particle arrangement. Thus, the grain boundaries in the particle assembly behave as displacement surfaces. Since the displacement along these surfaces is controlled by the normal force and frictional
coefficient acting on the surface, the displacement may be approximated as frictional gliding. This is grain-size independent and generally intermittent, causing so-called 'stick-slip' motion. Since the stick-slip motion occurs due to cycles of accumulation and release of elastic energy along the gliding surface, the force around the fault surface should be cyclically distorted. According to in-situ stress measurements by Nieuwland et al. (1999), low amplitude stress cycling after the initiation of a fault is observed in their thrust-and-fold belt sandbox experiments, interpreted as a stick-slip process in the fault zone. In cases where many faults exist, the distribution of the forces within the geological body will be affected by such distortion due to sequential fault events. The temporal variations in the particle velocity and forces are therefore presumably due to stick-slip behaviour along frictional surfaces.

Such temporal variations can be found in natural structures. Field and seismic observations clearly reveal that geological structures include many faults with a variety of directions even in a region that has been typically formed under a specific tectonic environment. Focal mechanism analysis of aftershocks also always shows such a variation even after one earthquake event (e.g., Shibazaki et al. 2002). This suggests that temporal variations of faulting are quite common in natural structures. The temporal variation may also be related to underground fluid flow. Sibson (1990) argues that the underground stress changes the permeability along fault surfaces, thus the variation in the force distributions may affect the fluid flow system along fault surfaces. The pattern and the paths of the fluid flow in accretionary prisms may be important controls on the accumulation mechanism of methane hydrates. The temporal variations seen in the model results can thus be a key to understanding the heterogeneous distribution of methane hydrates in accretionary prisms (i.e., Baba & Yamada 2004).

Velocity and force variations in natural geological bodies due to stick-slip behaviour of faults are not yet well investigated. The models shown in this paper can be used to understand such natural instability in the geo-environment. This technique might be applied to prevent possible future geo-hazards (e.g., Ueta et al. 2000), provided that the models are properly scaled and the magnitude, place and timing of possible earthquakes and related deformations are properly understood from the modelling results.

Conclusions

The analogue (sandbox) and numerical (distinct element method) models used to examine the effect of a décollement layer within sediments show that inserting a lower frictional coefficient layer reduces the slope angle and increases the fault spacing. This agrees with the critical taper theory (Davis et al. 1983). The geometric variations observed in the model prism may be explained by fault reactivations. The velocity and force directions extracted from numerical particles are instantaneous distributions and their temporal variations may be due to stick-slip behaviour of frictional gliding along grain boundaries. The active shear zone distributions interpreted from the stress directions of the numerical models predict possible fault curvatures within the prism, and agree with the numerical velocity vectors. The overall geometry of accretionary prisms with a décollement in the sedimentary pile is similar to the models, including the kinked geometry of the sequential thrust surfaces accompanied by backthrusting. The extensional stress regime under the décollement at Nankai is also explained by the numerical
stress distributions. This study shows that combinations of analogue and numerical models enable the extraction of more data from the results, that can be examined for detailed deformation characteristics.

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References


McCLAY, K. R. 1990. Deformation mechanics in analogue models of extensional fault systems.


