The role of indentation geometry in ramp – flat thrust orogenic systems. An analogue model interpretation

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ABSTRACT

In order to understand the mechanism of the thrust's and backthrust's creation i.e. when do they appear, when and why they seize functioning and what influences their number, we used an analogue model which is near to Merle and Abidi's 1995 model but it emphasizes on the formations which are provoked only by compressing brittle material, analogue to the upper (sedimentary) brittle part of the earth's crust.

Our principal intention was to investigate the role of two specific factors during the compression of our analogue model i.e. how those factors influence the creation of thrusts and backthrusts: a) angle of the rigid ramp, and b) thickness of the sand pack.

We conclude that the thickness of the sand pack is a negative factor as far as it concerns the creation of an effective indent. Models with thinner initial sand layering present more back thrusts on the rigid ramp while those with thicker initial sand layering present more backthrusts near to the rear wall. Models with a=30΄1 present more backthrusts than the other experiments show with the same d, but different a .

ΠΕΡΙΛΗΨΗ

Η διαδικασία της ορογένεσης είναι από τις πλέον πολύπλοκες τεκτονικές διεργασίες. Μια σημαντική διαδικασία κατά την ορογένεση είναι η ανάπτυξη ζωνών πτυχώσεων και επωθήσεων με συζυγή λεπιωμένα και ανάστροφα ρήγματα πλευρικώς βραχυνόμενα πάνω σε ένα ρήγμα αποκάλλησης (detachment fault). Πολλές ζώνες πτυχώσεων και επωθήσεων είναι ηπειρωτικά περιθώρια, όπου τα προς τη θάλασσα εκτεινόμενα πετρώματα της ιζηματογενούς σφήνας πτυχώθηκαν και επωθήθηκαν πάνω στο κρατογενές. Ένας πολύ αξιόπιστος τρόπος για την έρευνα αυτής της διαδικασίας είναι αναπαράσταση και μελέτη της με φυσικά αναλογικά πρότυπα (physical analague models).

Στην εργασία αυτή τα αναλαγικά μοντέλα δημιουργήθηκαν μέσα σε πειραματική διάταξη Plexiglass με διαστάσεις : α) 9.5cm x 7cm x 1cm και β) 9.5cm x 7cm x 1.9cm. Τα μοντέλα αποτελούνται από "παθητικά" στρώματα άμμου διαφορετικών χρωμάτων σε οριζόντια στρώση. Η άμμος προσομοιάζει στο θραυσιγενές τμήμα του φλοιού, παρουσιάζοντας με ικανοποιητική προσέγγιση τις ίδιες φυσικές ιδιότητες με αυτό. Η πειραματική διάταξη αποτελούνταν από τρία διαδοχικά επίπεδα: ένα οριζάντιο βασικό επίπεδο, ένα επικλινές και ένα δεύτερο οριζόντιο επίπεδο (flat-ramp-flat). Στο πίσω μέρος ταυ βασικού επιπέδου υπήρχε ένα έμβολο ταυ οποίου η σταθερής ταχύτητας κίνηση (moter) προκαλούσε την παραμόρφωση της άμμου. Η ταχύτητα της κίνησης του εμβόλου ήταν σταθερή για όλα το μοντέλα. Οι παράμετροι που άλλαζαν ήταν το πάχος της άμμου d (d=1-1.9cm) και η γωνία του κεκλιμένου επιπέδου a (a=15°-30°-45°).

Παρατηρήθηκε ότι αμέσως μετά την έναρξη της συμπίεσης, η πρώτη δομή που δημιουργήθηκε σε όλα τα μοντέλα ήταν μια "γωνιώδης πτυχή ανύψωσης" ή πολυκλινής ή "μαιανδρική" πτυχή (box fold) αποτελούμενη από ένα εμπρόσθιο κλάδο (fore-kink) και τον συζυγή του οπίσθιο κλάδο (back-kink), κοντά στον πίσω κινούμενο τοίχωμα. Η δομή αυτή παραυσιάστηκε και στην περίπτωση με μικρότερο ποσοστό συμπίεσης στα μοντέλα με μεγαλύτερο πάχος στρώματος άμμου. Αποδείχθηκε γεωμετρικά

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ότι η δημιουργία της δομής αυτής συμβαίνει σε συγκεκριμένη απόσταση από τον πίσω κάθετο τοίχωμα (σταθερό τέμαχος), ώστε η επιφανειακή εμφάνιση του πρώτου back-kink να απέχει από αυτόν 0.5cm. Η δημιουργία ως πρώτης δομής μιας "μαιανδρικής" πτυχής καθώς και η ταχύτερη εμφάνισή της στα μοντέλα με μεγαλύτερο πάχος εξηγείται από την αναλογία k (Smoluchowski number) βαρυτικών προς πλευρικών δυνάμεων, παίρνοντας υπόψη τις δυνάμεις τριβής (k=Fg / Fp).

Στα μοντέλα με d=1cm η δημιουργία της πρώτης δομής ακολουθούνταν από την εμφάνιση μιας δεύτερης "μαιανδρικής" πτυχής κάτω από την πρώτη προκαλώντας ανύψωση της αμμώδους σφήνας (sand wedge). Στα μοντέλα όπου d=1.9cm η πρώτη μαιανδρική πτυχή δεν ακολουθείται από μια δεύτερη αλλά από την εμφάνιση ενός 2^{ου} back-kink στο σημείο όπου αρχικά το 1^{ο} είχε εμφανιστεί. Στην περίπτωση αυτή, η αύξηση της Fg μέσω του βάρους της άμμου, ακολουθεί το σύστημα στο να «διαλέξει» να μετακινήσει μικρότερη μάζα (δημιουργία back-kink και όχι box-fold). Εκτός του d την παραμόρφωση του μοντέλου επηρεάζει και η γωνία της κεκλιμένης ράμπας a. Στα μοντέλα όπου η a ήταν 15° ή 45° και d=1cm παρατηρήθηκε η εμφάνιση μιας ενεργού επικλινούς (effective ramp) που είχε τη μορφή ενεργού "οδόντωσης" (effective indenter). Η προαναφερόμενη δομή δεν ενεφανίσθη ούτε στα μοντέλα όπου d=1cm και a=30° (η γωνία εσωτερικής τριβής της χρησιμοποιούμενης άμμου είναι 30°) ούτε και σε εκείνα όπου d=1.9cm. Συμπερασματικά το πάχος του στρώματος της άμμου αποτελεί αρνητικό παράγοντα για τη δημιουργία ενεργού επικλινούς (effective ramp). Παρατηρήθηκε ακόμη ότι τα μοντέλα με μικρότερο πάχος άμμου (d) παρουσιάζουν περισσότερους οπίσθιους κλάδους (back-kinks) δημιουργούμενα πάνω στην κεκλιμένη ή στην ενεργή ράμπα ενώ τα μοντέλα με μεγαλύτερο d εμφανίζουν περισσότερους οπίσθιους κλάδους (back-kinks) κοντά στον κινούμενο όπισθεν τοίχο. Τέλος τα μοντέλα όπου a=30° εμφανίζουν περισσότερους οπίσθιους κλάδους (back-kinks) πάνω στην κεκλιμένη ή στην ενεργή ράμπα απ' ότι τα άλλα μοντέλα που έχουν το ίδιο d αλλά διαφορετικό a.

Introduction

Orogenesis, a Greek term for the building of mountains, is one of the most complex tectonic processes known to Geoscientists. To field geologists the term orogeny represents the penetrative deformation of the earth's crust associated with phases of metamorphism and igneous activity along restricted, commonly linear zones and within a limited time interval (Dennis 1967, Burg and Ford, 1997).

An important process, in orogenesis, is the development of fold and thrust belts with conjugate imbricated reverse faults laterally shortened above a "decollement" or detachment fault (Keller and Pinter, 1996). These reverse faults or back thrusts accommodate the shortening and serially propagate forward along a decollement.

In this study our principal intention is to investigate the geometry of fore-kinks and back-kinks at ramp angles varying from 15 to 60 degrees during compression using Merle and Abidi 1995 experimental set up.

The questions to be addressed are:

a) the influence of the rigid ramp angle to the mechanics of the internal deformation of the fore and back kinks which evolve to thrust sheets , and

b) the role the sand pack thickness in the creation and evolution of the above mentioned structures.

This investigation will be limited to purely brittle systems.

2. Analogue models

2.1 Model construction and deformation

Our experiments were performed at the tectonic laboratory of the Department of Geology, Aristotle University of Thessaloniki. The type of models that have been investigated were of purely frictional material which represent the brittle part of the crust.

The models were built in a Plexiglas squeeze-box with dimensions a) 9.5 cm x7 cm x 1cm and b) 9.5 cm x7 cm x 1.9 cm. The models have been investigated according to their vertical height which was: a) 1cm and b) 1,9 cm .The models consisted of passive sand layers of different colours which sedimented,

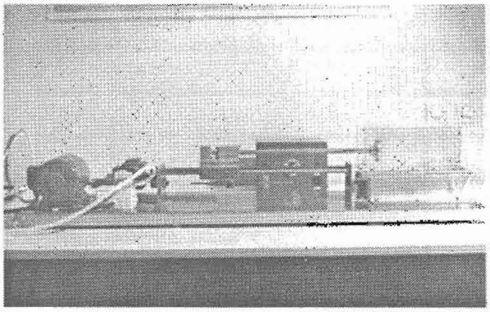
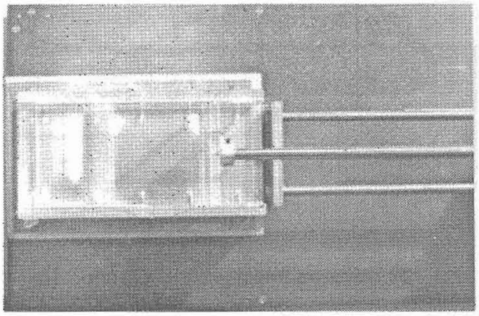



Fig.1

horizontally. The role of the colour layers was to visualize the internal deformation pattern in the model.

The apparatus comprised a fixed floor plate representing the basal flat and a dipping ramp of 15 - 30 – 45° in front of the flat (fig.1). Forward advance of a rear wall provides the convergence and hence the shortening of the sand pack. The rear wall was driven by an electric motor, at a constant rate of convergence of 1.25cm h^{-1}.

All models were deformed from 20%, 40% and up to 60% bulk shortening (%b.s.).Top view photographs were taken at constant time intervals during deformation.

2.2 Model materials

Pure quartz sand with particle diameters less than 0.246 mm was used in all models.

The sand is a Morh-Coulomb material with a mean density ρ_b = 1300 kg/m^3 which simulates the brittle behavior of sedimentary rocks. In laboratory tests this material shows an angle of internal friction φ = 30°, a coefficient of friction μ?= 0.6 internal and a cohesion c = 105 Pa.

2.3 Scaling of the models

The models are broadly scaled in a way that 1 cm in the model represents approximately 10 –15 km in nature. The models were focused on the deformation of the brittle upper crust decoupled from the lower ductile crust above a detachment represented by the Plexiglas floor of the squeeze-box. The velocity of the displacement, for Mohr-Coulomb materials, such as sand, which have a yield envelope essentially independent of strain rate, needs not to be scaled precisely.

The calculation of the velocity relationship between model and nature was based on Merle and Abidi, 1995. So, for v_m =1.23 cm/h, the velocity of the piston in the experiments, corresponds to v_n =1.78mm/y in nature. This value is comparable to that observed in natural thrust systems (Bonini et al. 2000 and references therein).

2.4 Limitations

Increase in vertical loading would normally result in isostatic adjustment and depression of the thrust plane. This factor was not taken into account.

The models were designed to focus on the brittle deformation of the upper crust and took no account of any ductile strain within the nappe pile. Temperature variations have not been considered either.

The moving wall that compressed the model was rigid and could not deform as the stronger plate might deform in nature. The models did not include the effects of erosion and sedimentation, only gravity spreading of the rising pile.

3. Results

3.1 Division of the experimental results

The experiments were divided into 6 groups. Every experiment of which belongs to the same group follows the same set up by keeping constant the following parameters, a) thickness of sand layers (**d**) b) length and width of the Plexiglas box, and c) dip of rigid ramp(**a**). The only parameter that we change is the percentage of bulk shortening.

Table A

Sand layer thickness (d):		1cm			1.9cm			
		Compression (%b.s.)						
Degrees (a°)		20	40	60		20	40	60
15	1st group	Exp.10	Exp.8	Exp.9	4th group	Exp.18	Exp.21	Exp.3
30	2nd group	Exp.7	Exp.4	Exp.6	5th group	Exp.12	Exp.20	Exp.17
45	3rd group	Exp.11	Exp.13	Exp.14	6th group	Exp.16	Exp.19	Exp.15

It must be noted that besides the experiments presented in Table A extra experiments have been carried out for clarification concerning the evolution of certain structures at specific stages of deformation. The parameters of these extra experiments are given below.

Exp.5: a=30º, d=1cm, %b.s.= 10
Exp.5a: a=30º, d=1cm, %b.s.=5.2

Exp.1: a=45º, d=1.9cm, %b.s =67.45
Exp.2: a=30º, d=1.9cm %b.s.=52.6

The description of the structures that occur during deformation of the models, separately for each group, will be presented below.

3.2 Description of the structures that occur during deformation of the models.

Experiments with d= 1cm

1st Group:

The first group of experiments took place when a rigid ramp of a=15° and thickness of sand layer d=1cm was used.

The following table I contains:

a) The appearance of fore- kinks and back-kinks at the surface of the sand pack as well as their approximate distance, in cm, from the rear wall that compresses the model.
b) The percentage of bulk shortening, when we observed each formation.
c) The number of fore- kinks and back-kinks.

Table 1

Experiment No	Fore-Kinks									
	1st		2nd		3rd		4th		5th	
	cm	%b.s.	cm	%b.s.	cm	%b.s.	cm	%b.s.	cm	%b.s.
10	3.5	3.1	3.6	14.7						
8	3.8	4.2	4	14.7	7.8	25.26				
9	3.8	4.2	3.8	14.7	11.5*	26.3				
	Back-kinks									
10	0.4	3.1	—	——						
8	0.7	4.2	—	——	3.8	25.26	3.2	40		
9	0.5	4.2	—	——	5.7	26.23	4.1	42.1	3.5	~60

* the fore-shear appears on the rigid ramp.

— : back-kink that did not appear at the surface.

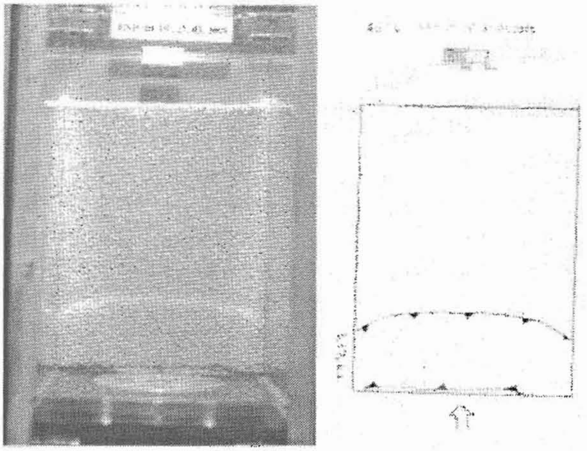


Fig.2

At 4 % b.s., the first box-fold, a simultaneous appearance of a kink and back-kink, occurred close to the moving wall forming an accretionary thrust wedge. It is noticed that the point of the box fold generation is not at the contact between the basal plate and the moving vertical wall but at a distance of ~ 2 cm in front (fig. 2).

A kink parallel to the first one was created at 14.7 % b.s., accompanied by a conjugate back-kink both being created at the same point where the first box-fold appeared. This can be illustrated in the cross-section of 20% b.s. (fig. 3a,b).

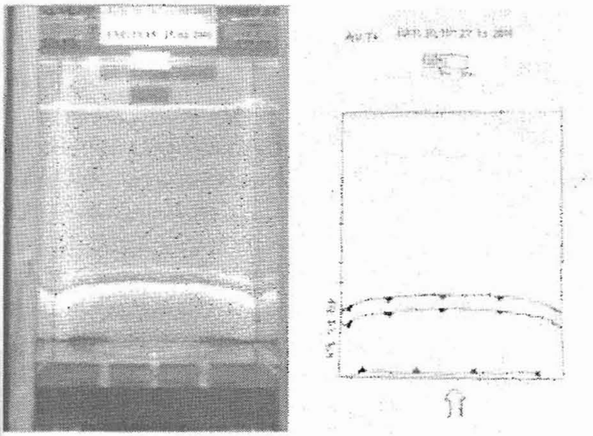


Fig.3a

When the amount of deformation reached the ~25 %b.s., a new box-fold occurred close to the toe of the rigid ramp. While the deformation of the system is concentrated at the new box-fold the former structures are passively carried towards the new created box-fold. The area between the two box-folds has the characteristics of a compressional basin.

As deformation continues, two more back-kinks were created one at 40% and the other at 60%b.s. which were formed in front of the

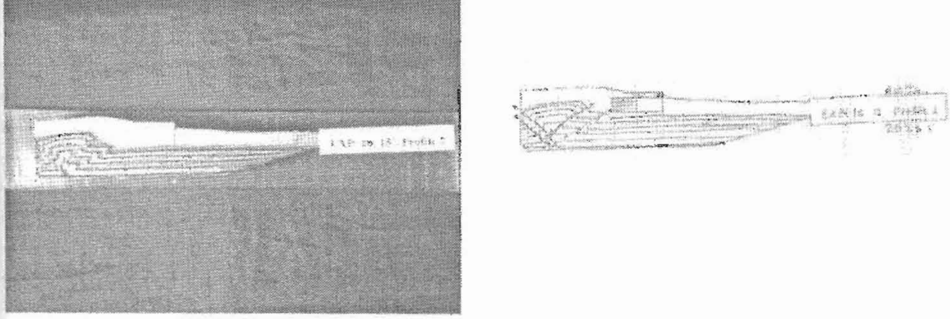


Fig.3b

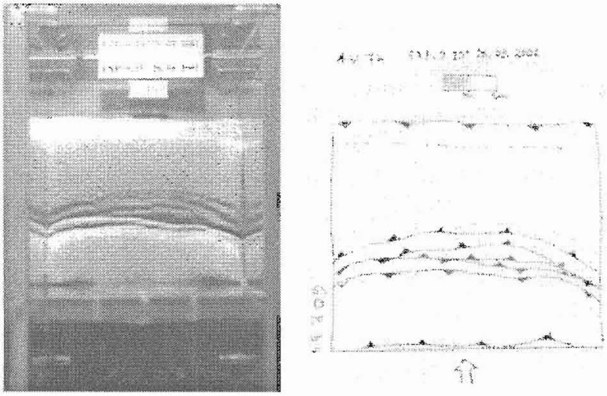


Fig.4a

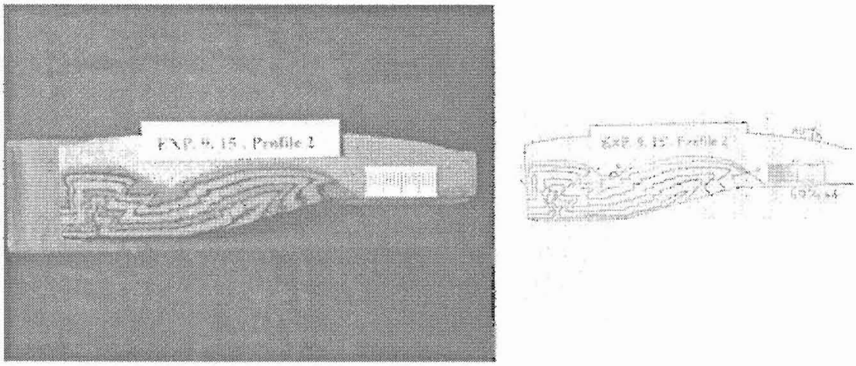


Fig.4b

Table 2

Experiment No	Fore-Kinks.													
	1st		2nd		3rd		4th		5th		6th		7th	
	cm	%b.s.	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s
5	3,2	4,2												
7	3,4	3,2	3,8	14,7										
4	3,7	4,2	4	16	8,8*	31,6								
6	3,8	4,2	4	15,78	9,1*	26,3								
	Back-kinks													
	1st		2nd		3rd		4th		5th		6th		7th	
	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s
5β	0,3	4,2												
7	0,4	3,2	---	---										
4	0,4	4,2	—	---	5,5	31,6	4,9	35,8	4,4	40				
6	0,6	4,2	---	---	5,2	26,3	5	34,7	4,4	36,8	3,9	41,05	3,2	54,7

* : movement along the ramp

— : back-kink that did not appear at the surface.

toe of the rigid ramp. The generation point of these back-kinks coincides with the point of creation of the second box-fold. At this stage of deformation what can be observed is that from the toe of the rigid ramp to the top of the ramp the sand pack does not glide along the contact but it builds its own ramp (fig4a,b). This structure is similar to the so-called 'effective indenter' discussed by Persson and Sokoutis (2001) and more detailed in Persson (2001). These two back-kinks are passively carried away from the toe of the rigid ramp along and above the spontaneous fore-shear which represents the upper part of the 'effective indenter' towards the upper flat area of the rigid ramp.

2nd Group:

Experiments with ramp angle a = 30° and sand thickness d = 1cm

The first box-fold appeared after ~4%b.s., as in group 1.

The second box-fold appeared approximately at the same distance from the rear wall, as the 2nd box-fold of the 1st group, but a little bit later at ~16% b.s instead of ~ 15% b.s..

At ~30%b.s, the creation of a new box fold has been observed and at the same time the sand pack slipped over the rigid ramp which was used as a decollement surface moving forward to the upper flat. A conjugate back-kink was created on the toe of the rigid ramp.. From that moment, the first box-fold stopped being active.

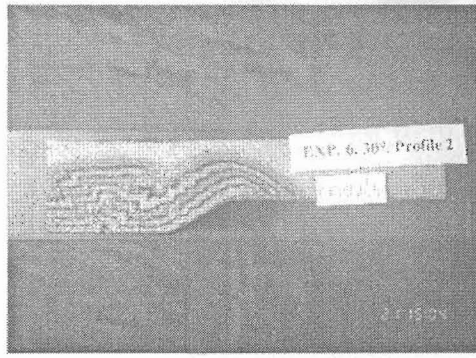


Fig.5

Three more back kinks were formed, at ~35%, ~40% and at ~55% b.s. respectively. All of them were formed at the toe of the rigid ramp and then transferred passively along the ramp. At 60% b.s the cross-section clearly illustrates that the fist kink evolved to a thrust *(fig. 5)*.

Foreland dipping normal faults started to appear at ~55%b.s. while with increasing bulk shortening, foreland-directed extensional collapse of the sand wedge above the upper flat of the rigid ramp became more developed. However, these normal faults for this %b.s. remain as superficial features and they are due to gravity sliding.

3rd Group:

Experiments with a= 45° and d = 1cm

Table 3

Experiment No	Fore-Kinks									
	1st		2nd		3rd		4th		5th	
	cm	%b.s.	Cm	%b.s.	cm	%b.s.	cm	%b.s.	cm	%b.s.
11	3,4	2,1	3,5	14,7						
13	3,5	2,6	3,7	13,7	4,1	24,7	6,8	34,7		
14	3,4	3,1	3,7	13,16	3,9	23,16	7,4	33,6		
	Back-kinks									
11	0,3	2,1	—	—						
13	0,5	2,6	—	---	3,3	34,7				
14	0,5	3,1	—	---	4,1	33,6	~2,8	54,2	~2,5	54,2

— : created but did not appear at the surface.

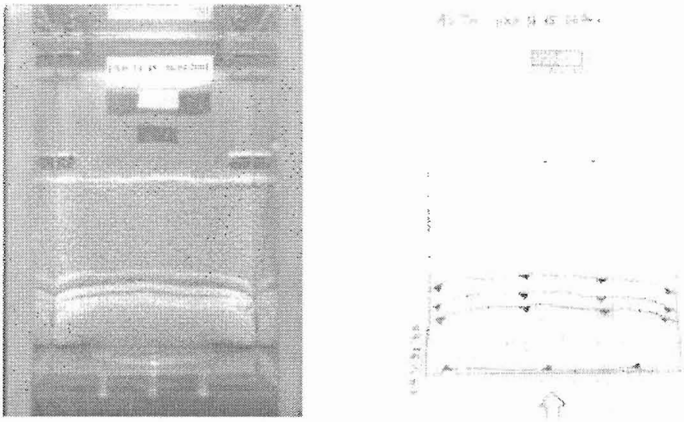


Fig.6

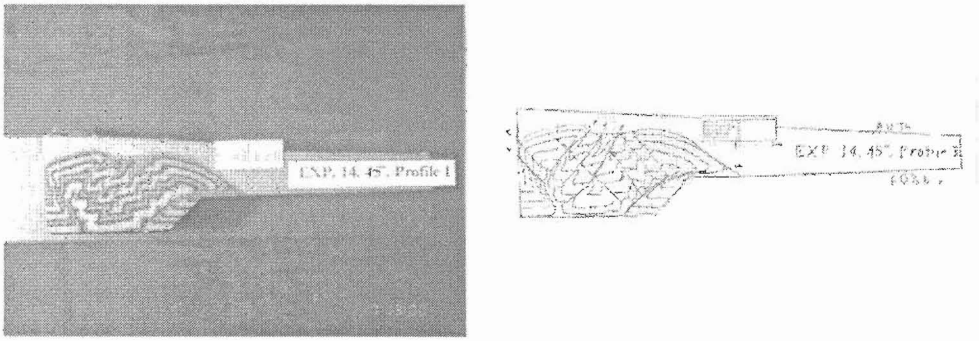


Fig.7

The first box-fold appeared near to the rear wall at approximately, 3%b.s., and by ~1% b.s. earlier than at the previous groups.

The second box-fold appeared after 13.5% of bulk shortening which is the same %b.s. as in the previous groups. At ~24%b.s. the formation of a kink took place, in front of the other two*(fig. 6)*.

The third box-fold appeared when the amount of bulk shortening reached the~34%.

From this point, the sand wedge climbed on

Table 4

Experiment No	Fore-Kinks					
	1st		2nd		3rd	
	cm	%b.s.	Cm	%b.s.	cm	%b.s.
18	6,1	2,2				
21	6,1	2,2	7,6	25,26		
3	6,2	3,2	6,7	22,1	13,3*	37,9
	Back–Kinks					
18	0,4	2,2	---	---		
21	0,5	2,2	---	---		
3	0,5	3,2	---	---	2,46	49,5

* : fore- kink appearance on the ramp.

—: created but not appeared on the surface.

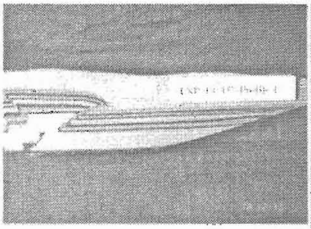


Fig.8a

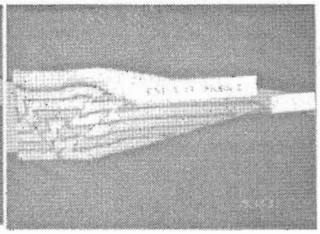


Fig.8b

the upper flat using as ramp the thrust located closer to the rigid ramp. So, this evolution gave birth to a new central sand wedge. This new formation is composed of: **a)** the 4[th] fore-kink which evolved to a thrust situated at the top of the structure that presents the characteristics of an 'effective indenter' and **b)** the first and second back-kinks, which were nearly joined forming a backward veregence shear zone 'semi-conjugate' to the thrust mentioned before *(fig. 7)*.

During the movement of the sand pack towards the upper flat, two more back-kinks created at the toe of the new ramp, and they appeared on the surface approximately at the same time ('54%b.s.).

***Experiments with* d= 1,9cm**

4[th] Group:

Models with a =15° and d =1.9cm

In this case, the first box-fold appeared earlier than at the previous groups (2,2%b.s.). The distance between the fore-kink, when it was created, and the rear wall was greater than in the groups of d=1 cm (i.e. 6.1cm while at the previous groups it was ~3.4cm). When the deformation is close to 20% b.s. the former fore-kink develops to a fore-thrust*(fig. 8a)*.

The second fore-kink appeared at 22-25%b.s.

The third kink emerged when the compression reached 37.9% of b.s. The slip plain was the dipping ramp.

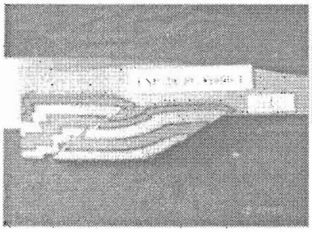
The first back-kink created at the toe of the rigid ramp, appeared on the surface after 45.9%b.s. As it can be observed in the cross-section of exp. 3, a second back-kink occurred at the toe of the rigid ramp but it didn't reach the surface*(fig. 8b)*.

Table 5

Experiment No	Fore-Kinks							
	1st		2nd		3rd		4th	
	cm	%b.s.	cm	%b.s	cm	%b.s	cm	%b.s
12	6,6	4,2						
20	6,6	4,2	10,6*	27,4				
17	6,8	4,2	10,5*	30				
2	6.87	3,1	7.1	23.16	10*	38.9		
	Back-Kinks							
	1st		2nd		3rd		4th	
	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s
12	0,5	4,2						
20	0,5	4,2	—	---	6	27,4		
17	0,7	4,2	---	---	3,7	40**	2,2	40**
2	0.3	3.1	---	---	1 48	48.4		

* : on the ramp

** : Simultaneous appearance of the 4[th], at the right side and the 3[rd] at the left side taking as a plane of reference the moving wall. The 4[th] back-kink appeared at the surface and evolved in a normal way while the 3[rd] did not evolve further even when the deformation reached the 60%b.s.



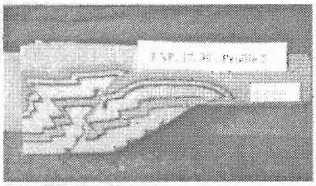


Fig.9

Fig.10

5th Group:

Experiments with a = 30° and d=1,9 cm.

The 1st box-fold occurred at 4,2% of bulk shortening.

The cross-section of exp. 12, at 20% b.s., demonstrates that the creation of the first box fold is immediately followed by a second back-kink created at the toe of the thrust which corresponds to the former fore-kink.

After ~30%b.s, a new box-fold appeared, having as spot of generation the toe of the rigid ramp. The slip plane of the surface was the rigid ramp.

The accommodation of the back-kinks is somehow more complicated because it presents a different behavior in each experiment. In experiment no 2 it appears at the surface without intersecting the first thrust*(fig. 9)*.

In experiment no 17 was observed that at 40%b.s. two back-kinks appeared. They occurred at the same time and at the same distance from the moving wall; the 3rd at the left and the 4th at the right side of the model taking as reference the moving wall. The 4th, grew some minutes after and became obvious while the 3rd remained as it was

Table 6

Experiment No	Fore-Kinks							
	1st		2nd		3rd		4th	
	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s
16	6,1	2,2						
19	6,2	4,2	6 ^	23,2	8,9*	35,79		
15	6,3	2,1	8,7*	33,7				
1	6	2.1	7.6	28	—*	~50		
	Back-Kinks							
	1st		2nd		3rd		4th	
	cm	%b.s	cm	%b.s	cm	%b.s	cm	%b.s
16	—	—						
19	0,6	4,2	—	—	2.2^*	40		
15+	0,4	2,1	—	—	3.4	36.8		
1	0	2.1	—	—	—	—	—	—

^ : A 2nd fore-kink appeared at the left side (reference –the moving wall), not fully grown. Possible boundary effect.

^* : This back kink is a typical one, created at the toe of the rigid ramp, but superficially it appeared only at the middle of the mode, near to the rear wall

+ : gravity collapse on the rigid ramp 6cm at 60%b.s.

* : fore-kink created on the ramp

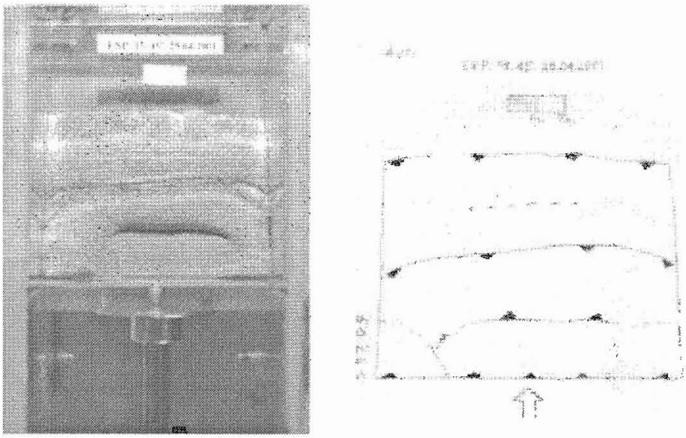


Fig.11

from the beginning, even after 60%b.s *(fig. 10)*.

In experiment no 2 the first back-kink created on the rigid ramp , intersected both the 1st and the 2nd kink and appeared at the surface 1,48 cm from the moving wall.

6th Group:

Experiments with a= 45° and d=1,9cm

The first box fold appeared at ~2.2%b.s. A second back-kink created behind the 1st but it didn't appear on the surface.

The majority of this group of experiments used the ramp for creating the 2nd fore-kink at ~35%b.s..

At ~40%b.s. the main back-kink created on the toe of the rigid ramp and appeared at the surface intersecting the previously formed fore-kinks.

Foreland dipping normal faults started to appear at ~50%b.s., and by increasing bulk shortening, foreland-directed extensional collapse of the sand wedge above the upper flat of the rigid ramp became more obvious *(fig. 11)*. In this particular case the collapse was not relevant to reactivation of back-kink as normal faults. It took place at the upper plane, as it was also observed in the experiment no 6.

Beside the above mentioned structures a number of minor structures were also observed which are noted at table.6.

4. Discussion

4.1 The first structure, the box-fold.

All experiments developed as first structure a box fold, independent of thickness.

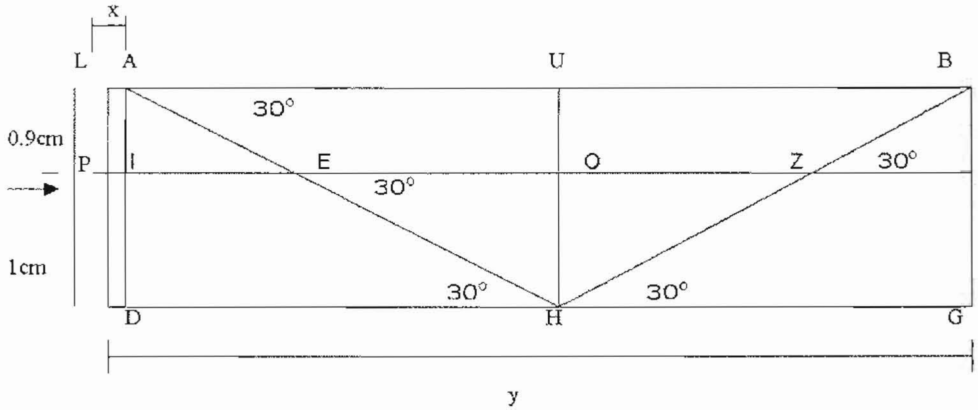
However, in general the models in where d=1cm, the first box fold appeared close to the rear wall at ~4.2%b.s., while in models with d=1.9cm the corresponding box-fold appears earlier at ~2.1 % b.s. Here we face two questions. The first is why a box fold has been preferred. This can be explained due to low friction detachments, the base of the deformation apparatus in this case, which requires wider spacing of structures. The second is why the thicker the pile the faster the appearance. To answer this we have to take into account the gravity and lateral forces as well as the shear resistance at the base of the pile. The shear resistance must be overcame by the lateral force in order to induce decollement which will provide the surface of movement. This ratio between gravity force/lateral force,κ, is known as the Smoluchowski number ($\kappa=F_g/F_p$).

Increasing the gravitational force the frictional force is additionally increased.

The higher the gravitational force is the more difficult becomes for the lateral force to move the whole system, so the system creates thrusts in order to move in smaller parts. In this particular case it was observed that models with greater thickness, d, present earlier the first box fold structure and this is logical because by increasing the d, the F_g increases and so the frictional force augments forcing the system to create thrusts earlier.

4.2 Second box-fold

After the creation of the first box fold, in the models with d=1cm, a second box-fold occurs below the first one giving rise to the sand wedge. The second



box fold has the fore-kink well developed while the back-kink is poorly developed. This can be easily explained by taking into account the moving rigid wall, which does not allow it to expand properly*(fig. 3b)*.

In contrast in models with d=1.9cm the creation of the first box-fold is never accompanied by the creation of a second one at the same place. Instead of that, it is observed in all cases, the appearance of a second back- kink at the same place where the first back kink was created. This phenomenon is due to the thickness of the sand i.e. additional weight and therefore higher F_g. The system prefers to use the first fore kink which developed to a thrust as a decollement surface at the base of which the back-kinks were created. These back-kinks travel passively along the thrust surface an arrangement that needs less energy to accommodate the deformation since it has to move a smaller mass*(fig. 8a)*.

4.3 Appearance of the 1st box-fold on the surface and its distance from the rear wall

The first fore-kink in models with d=1.9 cm rises on the surface in an approximately double distance from the rear wall, in comparison to the first fore-kink of the models with d=1cm. The internal friction angle of the sand is ~30°.

Assume that at the point P is the rear wall,

Where:

x : is the horizontal distance between the moving wall and the superficial appearance of the back-kink.

y : is the horizontal distance between the moving wall and the superficial appearance of the fore-kink.

A : point of appearance on the surface of the 1st back-kink created when d=1.9cm.

B : point of superficial appearance of the fore-kink

HB : fore-kink

HA : back-kink

PK : theoretical plain, 1cm above the lower flat DG

E, K : points where the back-kink and the fore-kink respectively intersect the theoretical plain PK.

Following the geometrical relationships :

OE = EH cos30° (1)

EH + EA = AH (2)

EA / EH = IA / ID (3)

AH = AU / cos 30° (4)

AU = (y – x) / 2(5)

Applying in equation 4 equation 5, the relationship becomes

AH = (y – x) / 2cos 30° (6)

It is known that:

IA / ID = 0.9 cm / 1cm => EA / EH = 0.9 / 1 =>EA = 0.9EH

EH + 0.9EH = (y – x) / 2cos 30° => 1.9EH = (y – x) / 2 cos 30° =>

EH = (y – x) / 3.8 cos 30°(7)

Since : OE = EH cos 30° => OE=(y – x) / 3.8

PE = PO – OE => PE = ((y - x) / 2) – ((y – x)

$/ 2d) =>$

$PE = (d-1)(y-x) / 2d$ (8) and

$PZ = PO + OZ = PO + OE => PZ = ((x-y) / 2) + ((y-x) / 2d) =>$

$PZ = (d+1)(y-x) / 2d$ (9)

Where, d = AD = 1.9 cm

If the aforementioned general model is cut horizontally at the plain PK (where the sand has d=1 cm), the new superficial appearance of the fore-kink will be at point Z whereas the appearance of the back-kink will be at the point E.

According to equations (8) and (9) the distance between the point E and the rear wall as well as between the point Z and the rear wall is respectively:

PE = 0,2368(y – x) and PZ = 0,763(y – x)

AD	X	y	PZ(Fore-Kinks) cm	PE(Back-Kinks) cm	EZ=PZ-PE
1,9	0,4	6,1	4,35	1,35	3,00
1,9	0,5	6,1	4,27	1,33	2,95
1,9	0,5	6,2	4,35	1,35	3,00
1,9	0,5	6,6	4,66	1,44	3,21
1,9	0,5	6,6	4,66	1,44	3,21
1,9	0,7	6,8	4,66	1,44	3,21
1,9	0	6,1	4,66	1,44	3,21
1,9	0,6	6,2	4,27	1,33	2,95
1,9	0,4	6,3	4,50	1,40	3,11
				Average :	3,09

The question to be addressed is:

If a compressed model which would have the same characteristics with the one mentioned above, but it would differ at the point that the latter model would have d= 1cm, would it be possible the 1st fore and back-kink of the latter model to appear at points Z and E respectively ?

From the experimental results extracted from the experiments of the 4th, 5th, and 6th group (d= 1.9cm), a table is constructed by using equations (9) and (8)

Experimental		
PZ'(Fore-kinks)	PE'(Back-Kinks)	EZ'=PZ'-PE'
3,5	0,4	3,10
3,8	0,7	3,10
3,8	0,5	3,30
3,4	0,4	3,00
3,4	0,4	3,00
3,8	0,6	3,20
3,4	0,3	3,10
3,5	0,5	3,00
3,4	0,5	2,90
	Average :	3,08

which presents the distance of points E and Z from the rear wall. This method is used in order to investigate whether the first box-fold at models with d=1cm is created at the same distance from the rear wall with the one created at models of d=1.9.

It is assumed that the first box-fold of models with d=1cm and d=1.9cm occurs at the same distance from the rear wall. Using equations (8) and (9), applied on the experimental results extracted from the experiments of the 4th, 5th, and 6th group (d= 1.9cm), a table is created showing the distance that the superficial appearance of the first fore and back-kink of a model with d=1cm should have from the rear wall, if our assumption is correct.

Table showing the position of kinks and back-kinks based in the above assumption:

	Experimental		
A/A	EZ=PZ-PE	EZ'=PZ'-PE'	Deviation
1	3,00	3,10	-0,100
2	2,95	3,10	-0,153
3	3,00	3,30	-0,300
4	3,21	3,00	0,211
5	3,21	3,00	0,211
6	3,21	3,20	0,011
7	3,21	3,10	0,111
8	2,95	3,00	-0,053
9	3,11	2,90	0,205
Average :	3,09	3,08	0,016

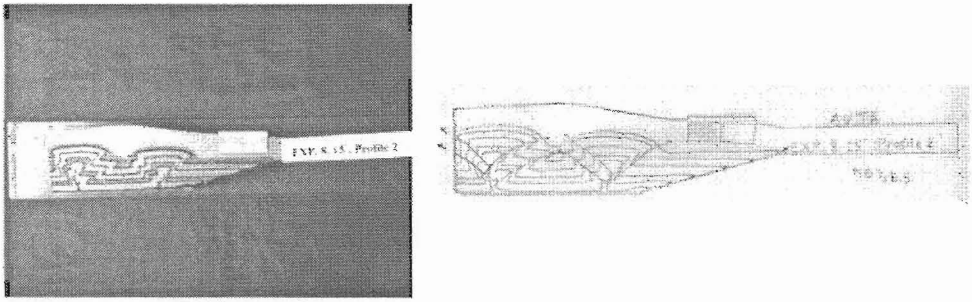


Fig.12

Table summarizing the distance of the first fore-kinks (PZ') and back-kinks (PE') created at the experiments of the 1st, 2nd, and 3rd group where d= 1cm:

The comparison of these two tables leads to the conclusion that the previous assumption was incorrect, i.e. the fist box-fold created at models with d=1cm and d=1.9cm do not occur at the same distance from the rear wall. The first box fold is created regardless to the sand thickness:

From all the above we conclude that the formation of the first box-fold (which was regardless to the thickness of the sand's layer), was realized in a specific distance from the rear wall so that the distance between the superficial appearance of the back-kink would be ~ 0.5cm.

4.4 The appearance of the effective ramp.

In the experiments with a= 15° and d=1cm, after ~25 %b.s., a box-fold was created near to the ramp. As deformation continued, the sand which was from the beginning at the front of the rigid ramp, did not move (only an upturn of the layering occurred), so that the system built up a sand ramp, creating a fold structure. This new sand ramp will be called 'effective ramp'. A similar structure was observed by Bonini et al. 1999 but in their work the rigid ramp was acting as indenter. As compression continued, several back-kinks were created at the toe of the rigid ramp in approximately equal time intervals*(fig. 12)*.

This effective ramp didn't appear at the models where a= 30° and d =1cm. In this case the sand pack used the rigid ramp in order to move the upper plain. The reason for this can be explained by taking into account the angle of internal friction of the sand, which is approximately 30° *(fig. 5)*.

At models where a = 45° and d=1cm an effective ramp was also created without causing folding to the layering of the specific part of the

Back-kinks						
				1 cm		
	compression (% b.s)	20*	40*	40#	60*	60#
dip (degrees)	15	2	2	2	2	4
	30	2	2	3	2	6
	45	2	2	1	2	4
				1,9 cm		
	compression (% b.s)	20*	40*	40#	60*	60#
dip (degrees)	15	2	3	1	2	1
	30	2	3	1	4	3
	45	2	3	1	3	2

* :created close to the moving wall

\# : created on the toe of the rigid or on the toe of the effective ramp sand pack *(fig. 4b)*.

In contrast to that, none of the experiments where d = 1.9 cm presented an effective ramp even when the bulk shortening reached the 60% *(figs. 8, 10, 11b,c)*.

4.5 Number of back-kinks.

In models with d = 1cm, the number of back-kinks created near to the moving wall which appeared in every model before 20%b.s., remains stable even after 60% of b.s. As the amount of the bulk shortening augments, at the toe of the rigid or the effective ramp new back–kinks occurred. The model where a = 30^0 presents more back-kinks (6 back-kinks) created on the toe of the rigid ramp during the movement than the models with a = 15^0 (4 back-kinks) and those with a = 45^0 (4 back-kinks).

On the other hand, the models where d= 1.9 cm tended to present less back-kinks than the models with d = 1cm. The back-kinks created at the toe of the rigid ramp were formed after ~40%b.s in the models where a = 30^0 or a= 45^0 and d=1.9 cm, and ~50%b.s. in the models where a = 15^0 and d=1.9cm.

Contrary to the models with d = 1cm, the number of the back-kinks created near to the moving wall was increased during the process of compression.

Models with d = 1.9 cm and a = 30^0 had the tendency to present more back-kinks than the models with a = 15^0 or a = 45^0, something which was also observed at the corresponding models with d = 1cm. The following table summarizes the above mentioned results:

4.6 Number of fore-kinks.

In models where d = 1cm, until 20%b.s. 2 thrusts appeared near to the moving wall, as mentioned previously, with their conjugate back-kinks.

At ~25%b.s. a 3rd fore-kink occurred close to the rigid ramp. In models with a= 30^0 this kink used the rigid ramp as sliding plain. Only in models with a= 45^0 a fore-kink kink which has the same area of generation with the first two appeared at 24%b.s. and then at ~35%b.s. it was observed the creation of a 4th fore-kink near to the rigid ramp which caused the formation of the effective ramp.

In models where d = 1.9 cm, close to the moving wall only one fore-kink occurred at ~4.2%b.s., while the second fore-kink appeared on the rigid ramp at ~26%b.s. When a= 15^0, before the appearance of the fore-kink on the rigid ramp (~38%b.s.) a fore-kink occurred near to the first one. Actually, this was the only model where despite the fact that d = 1.9 cm two box-folds were created at the same place near to the moving wall, a phenomenon that characterizes all the models with d= 1cm. The table below summarizes the above mentioned results:

Fore-kinks						
		1 cm				
	compression (% b.s)	20*	40*	40#	60*	60#
dip (degrees)	15	2	2	1	2	1
	30	2	2	1	2	1
	45	2	3	1	3	1
		1,9cm				
		20*	40*	40#	60*	60#
dip (degrees)	15	1	1	2	2	1
	30	1	1	1	1	1
	45	1	1	1	1	1

* :created close to the moving wall

: created on the toe of the rigid or on the toe of the effective ramp

5. Conclusions

1. In this experimental set up the formation of the1st box-fold close to the moving wall was regardless to the thickness of the sand pile. The aforementioned box-fold was created in a specific distance from the rear wall, which depends on the thickness of the sand pile.
2. When d = 1cm and the angle of the rigid ramp was a=15^0 or a=45^{0}an effective ramp was created to accommodate the deformation. In experiments where a=30^0 and d=1cm the model used as thrust plain the surface of the rigid ramp. When d=1.9cm, the formation of an effective ramp was not possible.
   This experimental work indicates that the thickness of the sand pack is a negative factor for the creation of an effective ramp.
3. Models with thinner initial sand layering present more back-kinks on the rigid or on the effective ramp while those with thicker initial sand layering present more back-kinks near to the moving wall.
4. Models with a=30^0 present more back-kinks on the rigid ramp than the other experiments with the same thickness, d, but different rigid ramp angle, a.

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