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2D Numerical Modelling for Understanding Crustal Deformations at Convergent Plate Margins

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Abstract

Continental subduction and collision normally follows oceanic subduction leading to enormous crustal deformations. For understanding this mechanism oftectonic plates in collision area, which may propagate into the subductioncollision transition zone is of great interest. At the locations of high-pressure metamorphism, some places form huge crustal deformations like between Indian-Eurasian plates, and subduction at other places like Indian-Burmese plates. In either of the casesdeformation is a continuous, dynamic process. To understand the process, a study has been carried out using two dimensional finite element modeling. With the current availability of computing technology, advanced numerical techniques and material models it would be an easy task to know the parameters effecting the transition from collision to subduction process between different tectonic plates. In this paper, simpleinclined models are used to study subduction-collision transition zone. Elastic material rheology is considered for all the tectonic plates and contact analysis is used for the tectonic plate interfaces for the implementation of weak zones. Parameters considered for this study are geometry of plates, friction at the interface and length of the plates. This study concludes that vertical surface displacements are largely effected by the considered parameters.

Keywords: Indian tectonic plate, FEM modeling, collision-subduction, crustal deformation.

Introduction

The theory of plate tectonics has evolved to be one of the most successful phenomenon explaining the behaviour of rigid tectonic plates floating around the earth's surface leading to different types of interactions (Convergent, Divergent and Transform). It also explains dynamic evolution of the lithosphere at the plate boundaries¹. One of the most dramatic and interesting interaction leading to different types of crustal deformations are found where tectonic plates converge. And convergent plate boundaries comprise both subduction and collision zones. At subduction zones geological andgeophysical observations suggest that convergence is accommodated by subduction of oneplate (oceanic plate) beneath the other (continental or oceanic plate). At collisional plateboundaries the colliding plates are both continental in nature, or one is continental and the other carries a magmatic arc². In simple the continental convergence (subduction/collision) normally follows the oceanic subductionunder the convergent forces of lateral 'ridge push' and/or oceanic 'slab pull'³. Geological and other observations show that vertical displacements of the Earth's surface near convergent plate margins may reach magnitudes of the order of hundreds of meters to several kilometres^{4,5}. Few examples are the Himalayan-Tibetan belt and the European Alps that are formed by direct continent-continent collision leading to highest peaks, another type where continental collision is highly oblique is at the Southern Alps of New Zealand, and the third different one is arc-continent collision found nearer the belts of Taiwan and the Timor-Banda arc in

the southwest Pacific leading to lesser vertical displacements. These vertical displacements may be caused by various processes that are related to plate convergence. For example, the initiation of subduction may lead to subsidence of the overriding plate to the order of a few kilometres⁶, while the termination of subduction will probably lead to uplift^{4,7}. Figure 1 shows the convergent plate margins all over the globe.

Few parameters that are affecting the evolution of continental collision zones are convergence rate, lithosphere rheology, buoyancy and inter plate pressure^{8,9}. In addition, De Franco^{10,11} pointed out that the most relevant parameter during the initial stage of continental collision is the geometry and (de)coupling along the plate contact. In that sense the plate contact is in an early stage decisive whether the lithosphere will entirely subduct, delaminate, or will not subduct at all¹⁰. To obtain subduction, Tagawa¹² suggested that weakening of the plate boundary is even more important than the rheology of the lithosphere which depends on many factors.One of the factorswhichplaya vital role at the contact of two tectonic plates is coefficient of friction making the interface weak or strong. It also effects the crustal deformation in both horizontal and vertical directions. This study concentrates on crustal deformation during the phase of ongoing convergence between oceanicandcontinental lying on lithospheric mantle. Major aim of this study is to quantify vertical surface displacements along the plate surfaces resulting from variations in plate geometry, friction, length and boundary conditions.



Convergent plate margins are marked in triangular shape over the tectonic plate boundaries and world political map as represented in legend. (Data: Peter Bird, 2003)

This study presents two cases of 2-D numerical models for collision and subduction zone dynamics on a timescale of a few million years. However the time scale is converted into displacement applied to the oceanic plate. All the three plates used for study are elastic, which leads to the use of an effective thickness. Plates with an effective thickness adequately simulate the surface deformation at a subduction zone¹³. One of the main advantage of numerical modelling in comparison with all other studieslike analogue models, observational models is a larger freedom in choice of material parameters, while stress and topography can be determined at all stages of the experiment.

Literature Review

Understanding continental convergent margin dynamics implies several different processes but near strictly correlated processes, such as continental deep subduction, HP-UHP metamorphism, continental collision, exhumation, and building of mountains. Apart from that, the systematic geological and geophysical investigations of the continental convergent zones, numerical geodynamic modelling becomes a key and efficient tool^{9,14-26}. Numerical modelling method can be used to i. testify the conceptual models generated fromnatural observations; ii. investigate the dynamics and mechanism of general continental subduction/collision; iii. study the controls/influences of important physical parameters on the geodynamic processes. The numerical models can be easily applied to investigate the geodynamical problems on variable spatial and temporal scales. Therefore, it is very convenient and can have significant implications for the geological observations.

Based on the wide numerical investigations, the tectonic styles of continental convergence can be summarized into the following six modes: pure shear thickening, folding and buckling, one-sided steep subduction, flat subduction, two sided subduction, and subducting slab break-off²⁴. These different modes can be attributed to variable thermo-rheological conditions of the converging plates, as well as the different boundary conditions, etc. The role of the plate boundary and its development during continental collision has been studied in both numerical and physical modelling studies^{10,11,27,28}. In most models the plate contact was represented by a predefined weak zone dipping 45° with respect to direction of shortening^{10,12,29-32}. The implementation of a weak interface separating the upper plate and lower plate with varying thickness, length and angle resulted in different styles of continent collision in terms of orogenic structure and topography.

2-D models are indeed relevant to study the general processes and dynamics in the continental subduction channels and/or the interior of the continental collision zones²⁴. But, not many numerical models deal with the change in geometry in terms of inclination angles for understanding the process of collision to subduction. This study focuses in the examination of vertical crustal deformation resulting from the oceanic plate colliding with the continental plate by considering the inclination angles and also the effect of friction at the interface between the two interacting platesresting on third plate in 2-dimensional. Our modelling is similar to other studies³³ carried for geodynamic modelling in terms of materials used and boundary conditions applied.

Numerical Study: To understand the effects of collision to subduction on surface displacement near convergent plate margins, 2-D numerical models are modelled on the scale of the whole lithosphere. The mechanical evolution of lithosphere on geological timescales is governed by the equilibrium equation:

$$\nabla \cdot \sigma + \rho g = 0 + \text{boundary conditions},$$
 (1)

where σ is the stress tensor, ρ is the mass density and g is the gravitational acceleration. This equation is solved using the finite element method based commercially available software ABAQUS/Standard (ABAQUS, 2011), which uses a Lagrangian formulation³³.

This study does not make predictions for any real continental subduction zone, but it focuses on understanding the physical process involved in the transition from collision to subduction. For this reason, generic models based on geometry are considered for analysis, where oceanic plate is collided and subducted underneath of continental plate. In considered models, collisions to subductions zones are represented by 2-D cross sections (figure 2-3). Although continental collision process have important 3-D features, the first order effects of convergence can be appreciated by analysing a characteristic cross section normal to trench. With this simplification this study assumes that the continent extends infinitely in the out of plane direction.

The two cases considered for this study have similar kind of meshing, and it is very fine at the contact interface. The elements have an average size of 5×5 km for the oceanic and 3×3 km for the continental plate respectively. And the plate

interface is modelled as the contact zone between the two separate meshes of the oceanic plate and continental plate. In both the case studies the coefficient of friction is increased uniformly from $\mu = 0$ to $\mu = 0.4$. A higher value of the friction coefficient is unrealistic for subduction systems as indicated by heat flow data and palaeo-geothermal gradients of high pressure/low-temperature metamorphic rocks.

In this study, analysis is done in two steps using ABAQUS; step1 boundary conditions are applied which includes restraints, constraints and contact interfaces between different tectonic plates, and in step2 displacement of 0.5 km is applied to whole oceanic plate for the two cases in 100 increments, so that the deformation profile can be seen for 100 increments. Both the models are assumed to have no initial stresses developed.

Geometry and boundary conditions

For understanding crustal deformation due to two plate's interaction leading to collision or subduction, 2D models are analysed and studied. Considered parameters are geometry, friction and length. This study considers only interaction between continental crust and oceanic lithosphere even though there are other kinds of convergences taking place in reality, study also assumes that oceanic lithosphere subducts under the continental crust.



a. Basic model setup of three plates Oceanic lithosphere, Continental crust and Lithospheric mantle, dotted line with (theta, θ) represents 11 different case studies. b. Model setup indicating contact interfaces (Interface1, Interface2, and Interface3) and boundary conditions

Case 1: Figure-2(a) represents the model setup of case study-1, where three tectonic plates, oceanic lithosphere, continental crust and lithospheric mantle are interacting with each other. This study majorly focuses on the interaction between oceanic lithosphere and continental crust. In each case study there are eleven sub cases based on the geometry that change with respective to theta (θ) or inclination angles as shown in the figure-2(a). That is oceanic lithosphere and continental crust interaction interface line is changed with respective to horizontal angle theta (θ). The angles considered for the study are divided into two sets based on angle increments, set1 with angle increment of 5^o and set2 with angle increment of 10^o. Set1consist of angles 20^o, 25^o, 30^o, 35^o, 40^o and 45^o. Set2

consists of angles 50° , 60° , 70° , 80° and 90° . And each sub case has five more cases based on coefficient of friction μ . Coefficient of friction μ values considered for this study are 0.0, 0.1, 0.2, 0.3 and 0.4. The length and thickness of the oceanic lithospheric are considered to be 200 km and 50 km respectively, whereas continental plate length is considered to be 400 km and thickness to be 50 km. Lithospheric mantle length is taken to be 600 km and thickness to be 50 km similar to other two plates and is maintained consistent throughout the analysis. Whereas, bottom lengths of oceanic lithosphere and continental crust are changed during every subcase, calculated using theta (θ).

 Table-1

 Interfaces properties considered, in contact type slip means slip is allowed and hard means no gap is allowed once two surfaces are in contact. Only for Interface3 friction coefficient is changed for sub case studies

	Interface 1	Interface 2	Interface 3		
Tangential Properties a. Contact Type b. Friction Coef	slip µ=0	$slip \\ \mu = 0$	No slip		
Normal Properties a. Contact Type b. Friction Coef	Hard -	Hard -	Hard -		



Finite element grid of the case1, lithospheric mantle plate has equal square elements whereas oceanic and crustal plates have quadrilateral elements because of the inclined plane

Table-2								
Material properties used for case studies 1, case study 2 and								
asso study 3								

case study 3									
	Continental	Oceanic	Lithospheric						
	Crust	Lithosphere	Mantle						
Density(0)	$27 \text{ x } 10^{11}$	$33 \ge 10^{11}$	33×10^{11}						
Density (p)	kg/km ³	kg/km ³	kg/km ³						
Youngs	$50 \ge 10^{15}$	120×10^{15}	120×10^{15}						
Modulus (E)	N/km ²	N/km ²	N/km ²						
Poissons ratio (U)	0.25	0.25	0.25						

Figure-2(b) shows the interaction types and boundary conditions applied to the model for analysis; there are three types of interactions defined. Interface1 is contact interaction between Oceanic lithosphere and lithospheric mantle, Interface 2 is contact interaction between Continental crust and lithospheric mantle, and Interface 3 is contact interaction between oceanic lithosphere and continental crust. More details about the interfaces and parameters used are given in the table-1. And for the boundary conditions bottom face of the lithospheric mantle is fixed in both the directions, and also right faces of both continental crust and lithospheric mantle are fixed as shown in the figure-2(b). Material properties used for the analysis are described in the table-2, in fact same material properties are used for case2 also. Figure-3 shows the finite element gird developed just before the analysis, same grid pattern is used for case2 also. Larger view of the grid shows that lithospheric mantle have uniform meshing pattern whereas non uniform meshing pattern is seen for both oceanic and continental crustal plates due to inclined surface.

Case-2: The model setup of case study-2 is similar to case study-1 except the lengths of continental crust and lithospheric mantle. The length and thickness of the oceanic lithospheric are considered to be 200 km and 50 km respectively, whereas continental plate length is considered to be 600 km and thickness to be 50 km. Lithospheric mantle length is taken to be 800 km and thickness to be 50 km similar to other two plates and is maintained consistent throughout the analysis. Whereas, bottom lengths of oceanic lithosphere and continental crust are changed during every subcase, calculated using theta (θ). Same interaction types and boundary conditions are applied to the model as in case study-1.

Results and Discussion

Case 1: Effect of angle / geometry and friction: In case1 as described earlier a series of numerical analysis are carried out with reference to geometry and coefficient of friction at the plate interfaces to calculate the crustal deformation in vertical direction. Results are shown in table-3, which gives the maximum displacements obtained for each angle and respective coefficient of friction value. In detail crustal deformation or vertical displacements profiles are plotted against the crustal length, which are shown in the figure-4 (a-f) for set1 and figure-5(a-e) for set 2. One of the few observations made from the obtained plots is that, there exists a location where all the profiles have got same vertical displacement, irrespective of coefficient of friction values, in detail the distance fromleft side of continental crust and vertical displacements are mentioned in table 4.



Vertical deformation of continental plate by changing (theta, θ) from 20⁰ to 45⁰, interface coefficient of friction is changed from 0.0 to 0.4 for each angle and length of continental crust is 400 km



Figure-5

Vertical deformation of continental plate by changing (theta, θ) from 50⁰ to 90⁰, interface coefficient of friction is changed from 0.0 to 0.4 for each angle and length of continental crust is 400 km

 Table-3

 Maximum crustal deformation values obtained in 'km' by numerical analysis for each angle (θ) and coefficient of friction (μ) values, for the case study1

μ,θ	20 ⁰	25 ⁰	30 ⁰	35 ⁰	40 ⁰	45 ⁰	50 ⁰	60 ⁰	70 ⁰	80 ⁰	90 ⁰
0	0.1081	0.1049	0.0903	0.0895	0.0858	0.0792	0.0708	0.0561	0.0447	0.0313	0.0366
0.1	0.0966	0.0927	0.0799	0.0786	0.0753	0.0683	0.06	0.0473	0.0356	0.0233	0.0362
0.2	0.0866	0.0821	0.0706	0.0684	0.0651	0.0583	0.0505	0.0381	0.0268	0.0189	0.0358
0.3	0.0776	0.0726	0.0619	0.0588	0.0554	0.0484	0.0408	0.0291	0.0203	0.0162	0.0356
0.4	0.0695	0.0638	0.0535	0.05	0.0459	0.0392	0.0309	0.0216	0.0173	0.0144	0.0354

Table-4

Same vertical displacement is found for each angle (θ) but for different friction coefficients (μ), L_D (km) represents distance from left side of continental crust and V_D (km) represents vertical displacement at L_D (km)

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θ	20^{0}	25^{0}	30^{0}	35^{0}	40^{0}	45^{0}	50^{0}	60^{0}	70^{0}	80^{0}	90 ⁰	
$L_{D}(km)$	164	140	124	112	105	104	95	88	87	81	5	
V _D (km)	0.029	0.0264	0.025	0.0232	0.0221	0.0195	0.0191	0.0182	0.0169	0.0162	0.0366	

From figure 4 (a-f) it can be observed that, as the angle is increased from 20^{0} to 45^{0} the maximum crustal deformation is reduced from 0.108 km to 0.0792 km, in terms of percentage it is reduced from 21.6 % to 15.84 % when coefficient of friction is zero. These percentages are calculated with respective to given horizontal displacement. As in this case, the total horizontal displacement given to oceanic plate is 0.5 km.The maximum vertical deformation/ vertical displacement are found to be 0.108 km which is 21.6 %. Similarly the percentages can

be calculated for all the angles. When coefficient of friction is 0.1, the vertical deformation is 19.32 % for 20^{0} , 18.54% for 25^{0} , 15.98 % for 30^{0} , 15.72% for 35^{0} , 15.06 % for 40^{0} and 13.66 % for 45^{0} . So it directly indicates that as the angle of subduction with respective to horizontal increases the vertical deformation will reduce.

Other clear observation from figure 4 (a-f) is that as the angle is increased from 20° to 45° uniformly by 5° , the reduction in

maximum vertical displacements for each angle for coefficient of friction ranging from 0 to 0.4 is uniform for all the angles 20^{0} , 25^{0} , 30^{0} , 35^{0} , 40^{0} and 45^{0} . It also means that as friction coefficient increases deformation decreases which is quite normal as the shear force is developed between the interface, that could restrict to smaller elevation, due to decrease in slip between the interfaces. As friction coefficient increases the shear bonding between the interfaces increase even though it is a weak plane. If at all the slip occurs than it will occur in this weak region.

Table 4 indicates for each angle for different coefficients of friction their lies a point where all crustal deformation vertically have same elevation point. After that point the behaviour of plates are changed, that is the plate which has the maximum displacement before that point has the least displacement after that point which is clearly seen in figure-4 (a), but this difference is decreasing as the angle is increased form 20° to 45° . This also indicates the formation of multiple nappes in reality as angle increases there is possiblity of a single fault plane even though the frictional properties are different due to material properties, thermal properties and pressure. And this phenomenon and observation from the figure-6 is different, unlike the angles from 20° to 45° , the pattern is different for the angles 50° to 90° , infact there are no multiple crustal deformation found after a point for different coefficients frictions. This also indicates the tranformation from subduction to collision, since only a nearer part is getting effected.

Another observation which is quite different when compared 20° to 45° and 50° to 90° is, there is no more uniformity in the maximum vertical deformation for different coefficients of friction that could be clearly seen in the figure 5(c) and figure 5(d). As the angle is increasing the nappe formation is uneven, that is in comparison for the angle 70° , vertical displament when $\mu = 0.4$ and $\mu = 0.3$ is very less compared to $\mu = 0.3$ and μ =0.2. And suprisingly this difference is almost negligible in the case of 90° , which is complete collision and effect of friction zero. And vertical displacement caused by 90° , is little greater than 80⁰. In all the numerical experiments carried out for this case study, there is buldge effect which is seen in all the plots except for the angle 90° . One of the reasons for this buldge effect is the effect due to fixed boundary, to understand the effect, length of continental plate and lithospheric mantle are increased by 200 km and results are discussed in case study 2.

For the case where angle is 90^{0} , it is also called as complete collision model since there is no percentage of subduction. Only for this case the results are quite different when compared to all other results, even though few imortant points are discussed in earlier this dimension of understanding is very important especially when two plates are about to converge. This type of situation arises when two plates of same thickness are about to collide, and the results obtained are for collision situation. As it

can be observed that, only in this case complete crustal plate is effected and crustal deformation is reduced uniformly through out the continental crustal plate.

Figure 6 (a)-(e) shows the plots for understanding the crustal deformation with respective to angles, for the same coefficient of friction. It clearly indicates that as the coefficient of friction is increased the crustal deformation of 90⁰ is also increased in comparision with other angles. Considering case where μ =0, maximum displacement of 90⁰ and 80⁰ are almost similar, when μ =0.1 maximum displacement of 90⁰ and 70⁰ are almost similar, when μ =0.2 maximum displacement of 90⁰ and 60⁰ are almost similar, when μ =0.3 maximum displacement of 90⁰ and 50⁰ are almost similar and when μ =0.4 maximum displacement of 90⁰ and 50⁰ are almost similar.

Case 2: Effect of length: All the results obtained by increasing the length of the continental crust and lithospheric mantle plates by 200 km towards the right side as shown in the figure are similar to the results obtained in case 1, but there are few differences too. When length is more considering 20^0 , the deformation profile after a point is constant but in the case where length is short the profile has changed, the one which had the maximum vertical deflection had least deflection after a common point mentioned in table-4, also this behaviour is little different when considered for all angles. Results are shown in table-5, which gives the maximum displacements obtained for each angle and respective coefficient of friction value.

In case 120° to 45° , the profiles have changed after a common point mentioned in the table 4, and for 50° to 90° the deformation profile almost remains same. But in case 2 it is vice versa for 20° to 45° , the crustal deformation profiles remain constant after a common point and for 50° to 90° the deformation profile have changed after the common point which are shown in the figure 7 and figure 8. When all angles are compared in case one, it is seen that maximum crustal deformation decreases from 20° to 80° , where as in case 2 it is completely reverse the maximum vertical deformation is increasing from 20° to 80° .

Comparing figure 6 and figure 9, in figure 6 there are no cross overs of deformation profiles for all the angles except by the profile where angle is 90° . Whereas in figure 9 or case2 there are multiple cross over by various angles, if clearly observed the cross over profiles are of angles 50° to 90° . So, there is effect of length on the collision to subduction patter and whole dynamics will change when length varies. Shorter length will give rise to uniform variations of weak planes and crustal deformations when compared longer length tectonic plates. But behaviour of 90° is very much similar in both the cases even though the maximum vertical deformations are different.



Figure-6

Vertical deformations compared for different angles friction being constant for each case and length of continental crust is 400 km



Figure-7

Vertical deformation of continental plate by changing (theta, $_{\theta}$) from 20⁰ to 45⁰, interface coefficient of friction is changed from 0.0 to 0.4 for each angle and length of continental crust is 600 km



Figure-8

Vertical deformation of continental plate by changing (theta, $_{\theta}$) from 50[°] to 90[°], interface coefficient of friction is changed from 0.0 to 0.4 for each angle and length of continental crust is 600 km



Vertical deformations compared for different angles, friction being constant for each case and length of continental crust is 600 km

Table-5								
Maximum crustal deformation values obtained in 'km' by numerical analysis for each angle ($ heta$) and coefficient of								
friction (μ) values, for the case study 2								

r	0	. 0	0		0		. 0		. 0	0	0
μ,θ	20	25"	30 °	35"	40 ^o	45°	50°	60 [°]	70 °	80 [°]	90°
0	0.1798	0.2242	0.2645	0.3053	0.3412	0.3642	0.3445	0.3039	0.2389	0.1102	0.0341
0.1	0.1768	0.218	0.2537	0.2869	0.3137	0.3257	0.2977	0.2478	0.1723	0.056	0.0337
0.2	0.1737	0.2119	0.243	0.269	0.2876	0.2895	0.2551	0.1979	0.1099	0.0179	0.0335
0.3	0.1707	0.2057	0.2324	0.2515	0.2621	0.2549	0.2158	0.1502	0.0491	0.0142	0.0333
0.4	0.1677	0.1995	0.2218	0.2344	0.2375	0.222	0.1768	0.096	0.0159	0.0123	0.0332

Conclusion

This study of simple 2 dimensional finite element modelling emphasizes the importance of the plate geometry on the topographic evolution of collision zones. The geometry of the plate contact together with the abundance and distribution of frictional properties along the contact interfaces controls the surface deformation and subduction process. Vertical interaction of continental plates as in case of angle 90⁰ will lead buckling of continental crustal tectonic plates and also the formation of folds. Inclined boundaries lead to under thrusting of the lower plates, but not necessarily subduction.

Series of models analysed during this study on continental collision with adjacent oceanic lithosphere simulated differently, yet linked various tectonic styles. Three major factors effecting continental deformation from this study are geometry of the plate (inclinations with respective to horizontal), length of the plate and coefficient of friction between the interfaces, all have their unique styles leading to the continental deformation. Firstly the behaviour is completely different when deformation is compared with long and short continental crustal plates. Secondly, if plate is shorter than weak planes would be formed more for the inclinations 20° to 45° , if plate is longer than possibility of weaker planes would be formed for their inclinations more than 45°. This simple study has given lot of insights for crustal deformation at the convergent margins especially between oceanic and crustal plate.

This study has shown that significant vertical crustal deformations at convergent plate margins may occur during collision and subduction. It has also quantified these deformations both in terms of magnitude and percentages compared to given horizontal displacements for a given inclination effective plate thickness.

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