2. MODELLING OF GEOLOGICAL HAZARDS AND RESOURCES

2.1 Crustal Deformation using Global Positioning System (GPS)

Crustal deformation studies initiated in 1994 for South India and in 1995 for the Himalayas were pursued further in 1997. Re-measurements were carried out at points in Southern Indian peninsula, Port Blair, and Garhwal Himalaya. Data was collected at each site for 3-4 days, 24 hours a day. The measurements sites include Suki, Chamba, Munsiyari, Almora and Delhi (in collaboration with Wadia Institute of Himalayan Geology, Dehradun). The station at Almora is being measured continuously since Dec 1997 in active collaboration with G.B.Pant Institute of Himalayan Environment and Development at Katarmal, Almora. Sites in South India include Ponnarkulam, Chennimalai, Mijar, Nanmangalam, Krishna-makonda, Devarabetta, Kannur, Rangaswamibetta, Kodaikannal, Manparai, Palghat and Palni. Re-measurements were carried out at Port Blair too. Data were analysed to estimate the convergence rate of the observation points in the Himalaya with respect to the observation point in the Indian Institute of Science, Bangalore and to analyse the stability of the South Indian Peninsula. Bernese 4.0 software package using the IGS precise orbits and pole parameters were used in processing. All the points were referenced to ITRF96.

The results show that the Bangalore-Delhi baseline convergence in the last 2.5 years (linear strain rate of 0.0035 microstrain/year), is small suggesting that the Indian plate between Bangalore and Delhi is relatively stable. However the two points in Garhwal Himalaya, one in Chamba (CHAM) just north of the main boundary thrust and one in Sukhi (SUKI) north

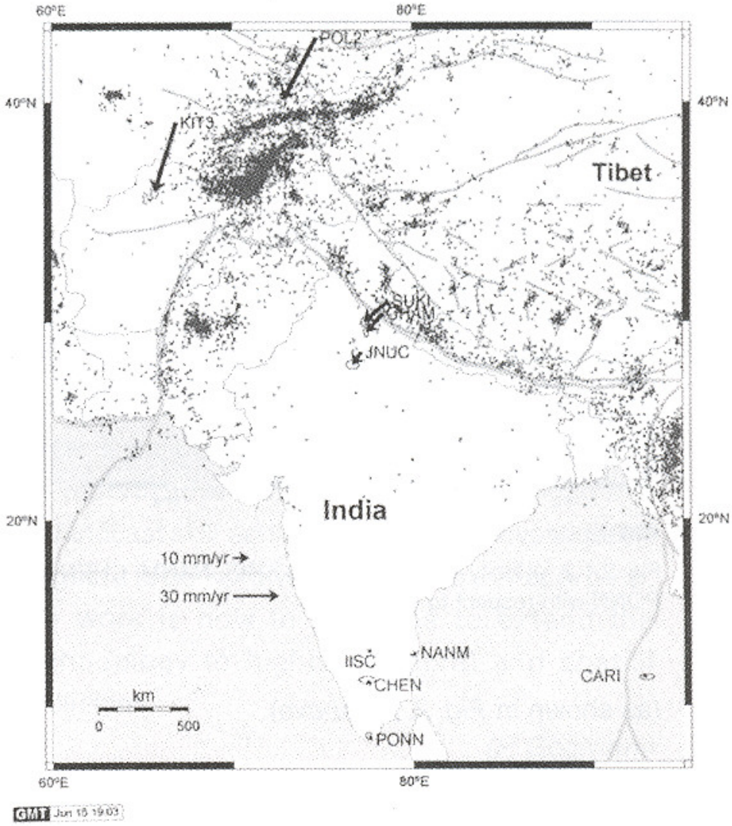

Fig. 2.1.1. Velocity vectors of points SUKI, CHAM, JNUC, POL2 and KIT3 with respect to IISc.

of main central thrust are converging towards the Indian plate at a rate of 14 mm/yr and 18 mm/yr, as shown in *Fig. 2.1.1.* Two points in the Eurasian plate were also used in the analysis and the convergence of these points with respect to Bangalore are shown in *Fig. 2.1.2.*

Analysis of four south Indian points (Chennimalai, Nanmangalam, Krishnamakonda, and Ponnarkulam) with respect to the Bangalore station (IISc) was carried out. Data collected in April 1995 and October 1997 were used for this analysis. Results suggest an average linear strain rate of 0.001 microstrain / year during the last 2.5 years. This, to some extent, indicates the stability of the south Indian peninsula. There is also an indication of volumetric strain of the south Indian peninsula

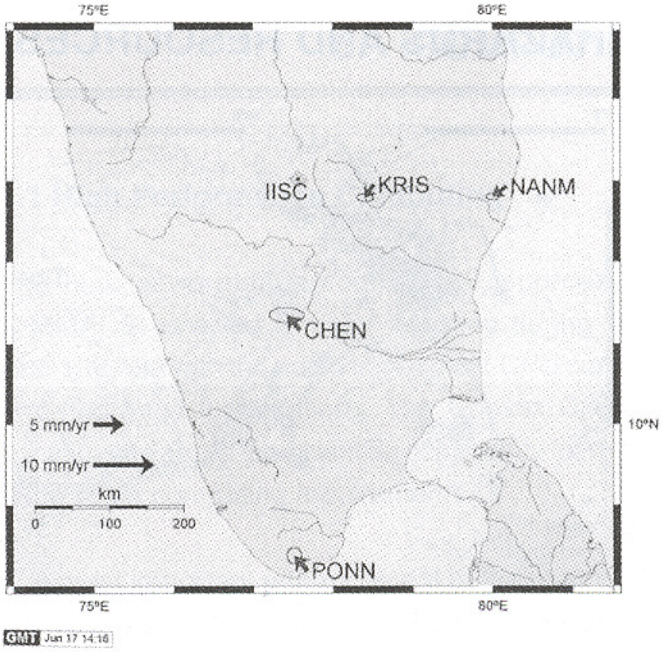

Fig. 2.1.2. Velocity vectors of points KRIS, NANM, CHEN and PONN with respect to IISc.

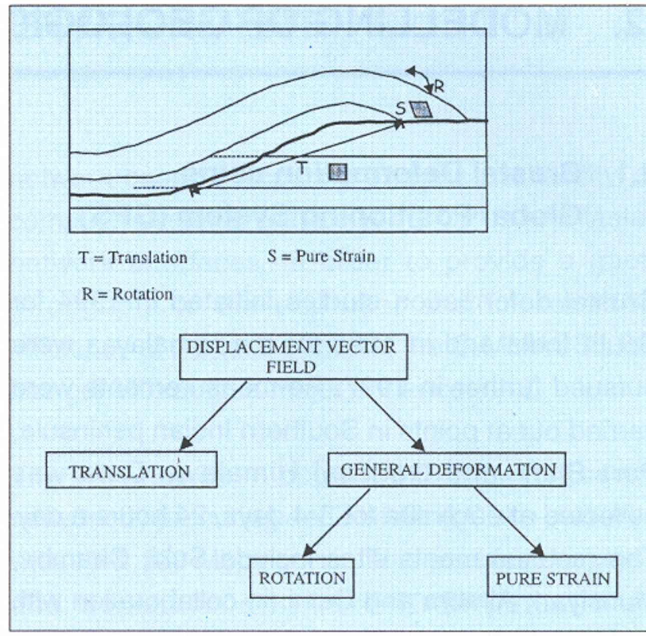

Fig. 2.2.1. The main components of the displacement field for emplacement of a thrust sheet. The pure strain component is usually not removed in the construction of retrodeformable cross-sections.

(as shown in *Fig. 2.1.2 above*).

These results which would be finalised after another epoch of measurements in 1998 will be significant for estimating the earthquake hazard in India. These results would also have implication to understanding the dynamics of the Indian lithosphere.

(J.Paul, M.B.Ananda, Dileep Kumar, V.K.Gaur, Sridevi Jade, and P.K.De)

2.2 Modelling of Deformation in Orogenic Mountain Belts

A new integrated methodology is being developed and applied to study the deformation in parts of the Indian Himalayan mountain belt (Darjeeling-Sikkim Himalayas) as part of the lithosphere modelling activities. This methodology aims at integration of conventional field geology along with laboratory work, GPS (global positioning system) geodetic techniques and finite element modelling/computer simulation. The generated data will be analysed in the light of the critical wedge theory for a better understanding of the evolution of the geometry and kinematics of the Darjeeling-Sikkim fold-and-thrust belt, and orogenic mountain belts in general, along with the wedge-mechanics in this part of the Himalayan mountain belt. The focus of the present study is on individual thrust sheets which combine together to form the Himalayan fold-and-thrust; the thrust sheet (and its associated thrust fault) is regarded as the basic structural unit for this methodology and deformation within an individual thrust sheet is represented by the associated displacement vector field (*Fig. 2.2.1*).

Computer-aided retrodeformable models of the evolution of the geometry and kinematics are being routinely used in industry and academia to understand deformation in fold-and-thrust belt settings. This is aimed at conceptually retro-deforming the finite configuration of a fold-and-thrust-belt to its undeformed state (*Fig. 2.2.2*). However, this technique is based on the assumption that either the length or the area or a combination

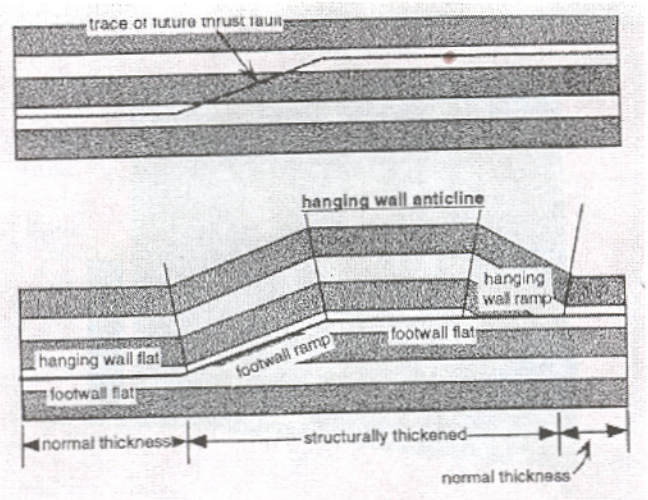

Fig. 2.2.2. Retrodeformation of finite deformation in a thrust sheet (a) to its undeformed state (b) based on removal of the displacement vector field assuming plane strain. This technique is valid for deformation in external parts of fold-and-thrust belts where finite strain part of the displacement vector field is absent or satisfies plane strain. However, the plane strain condition is no longer satisfied in internal parts of fold-and-thrust belts due to superposed deformation resulting from more than one penetrative-strain producing deformation events.

of the two in the plane of cross-section is conserved between the deformed and undeformed configurations. Therefore, assumed deformation within each individual thrust sheet in a fold-and-thrust-belt is limited to flexural-slip for one-dimensional bodies (linear or curvilinear) and plane strain for two- or three-dimensional bodies. In the present work towards developing the integrated technique, the validity of the above assumption in the light of recent strain data from thrust sheets from several fold-and-thrust belts has been examined. An analysis of the strain data and subsequent mathematical modelling indicates that the plane strain assumption is violated near fault zones and in thrust sheets with more than one penetrative-strain producing deformation events. These results indicate that the current method for the construction of retrodeformable models of deformation in fold-and-thrust belts is not valid for the internal thrust sheets and alternative methods need to be developed. We are currently attempting to simulate the general strain and displacement patterns in individual thrust sheets using non-linear finite element methods as the next step in understanding the reasons why the plane strain condition breaks down in the internal thrust sheets. Preliminary models have been directed at understanding plane-strain deformation at mid-crustal (around 15 km) levels. A two-dimensional (using plane-strain elements) model of a quadrangular quartzite (treated as materially non-linear elasto-plastic material) body is subjected to displacement, pressure and force boundary conditions observed at mid-crustal levels. Tectonic shortening was initially taken up to build a topographic surface. However, the mechanism by which the surface was built is a function of the basal slope angle. For models with very low basal slope angle, the topographic surface was built by overall plastic strain in the body (*Fig. 2.2.3b*); maximum shear stresses were low in the body (*Fig. 2.2.3a*). This indicates that strain is the dominant component of the total displacement vector field in these situations.

For higher basal slope angles the topographic slope is built by probable nucleation of a fault near the base of the deformed body as suggested by the distribution of maximum shear stresses (*Fig. 2.2.4a*). This pattern also suggests formation of a 'horse' at the base of the deformed body which in turn suggests that, under the modelled conditions, formation of a duplex to enhance wedge taper is the most likely response of the deforming body (with high basal slope angle) to the tectonic shortening. The strain in this situation is mostly confined to the area forming the topographic taper and the basal horse (*Fig. 2.2.4b*). These results agree with observational studies in fold-and-thrust sheets where critical taper for forward advance of a deforming wedge has been observed to be built by strain within thrust sheets or duplex formation.

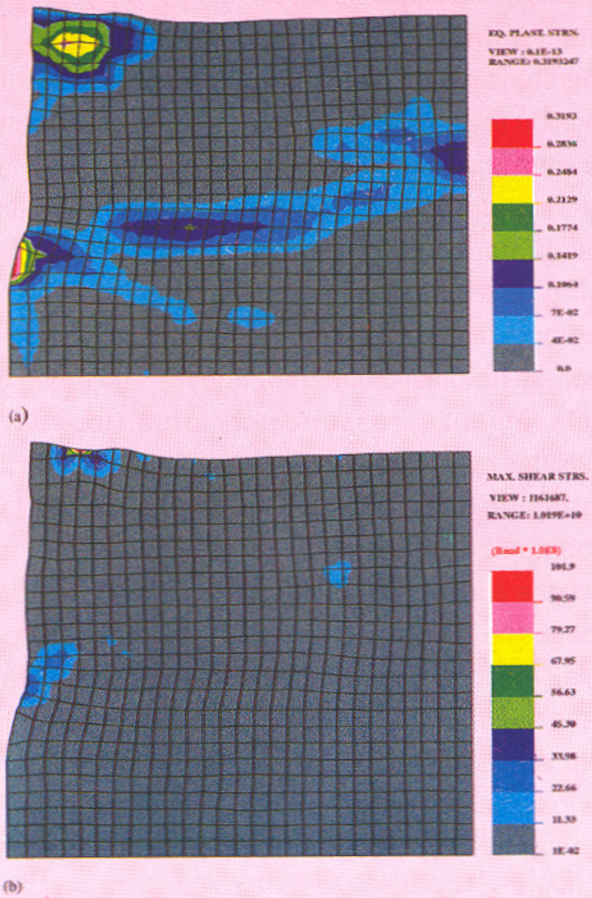

Fig. 2.2.3. (a) Strain distribution in a non-linear finite element model of a quartzite body under mid-crustal conditions with very low basal slope angle. (b) Maximum shear stress pattern in the same model. The patterns indicate that plastic strain was the dominant topographic slope building mechanism in themodel.

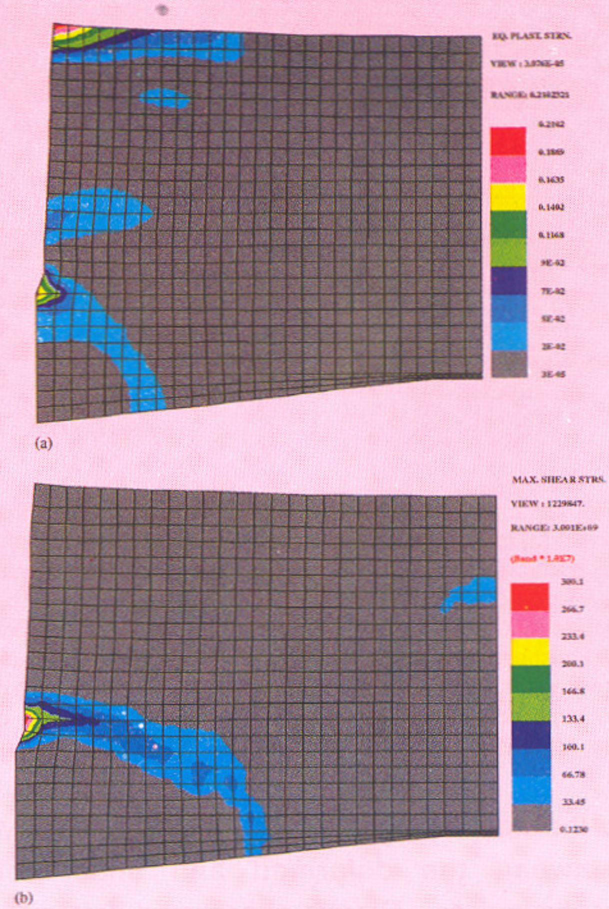

Fig. 2.2.4. (a) Strain distribution in the same model but with a basal slope of about 9 degrees. (b) Pattern of maximum shear stress in a non-linear finite element model and the location of a shear zone. The pattern suggests that duplex formation is the dominant topographic slope or taper building mechanism in this model.

The best approach for building the integrated methodology is to sub-divide the work into several components and gradually build the data base for final integration and interpretation. Using this approach we have begun studies on the main boundary fault zone in the Darjeeling area. Field observations indicate that the fault transports Gondwana age sediments on deformed Siwalik rocks, which is fairly well exposed in the area, and is characterized by cataclasite (cemented and uncemented) suggesting brittle deformation along the fault zone. We are currently studying deformation features at the microscopic scale from preliminary samples to understand the deformation characteristics within the fault zone and plan future fieldwork and sample collection in the zone. GPS stations have also been selected on the hanging wall of the main boundary fault and initial measurements have been made at these stations with an aim to determine if the fault is active at the present time.

(Malay Mukul)

2.3 Non-Linear Modelling of Jointed Rock

Nonlinear finite element analysis of jointed rock has been carried out as an equivalent continuum whose properties represent the material properties of the jointed rock. The material properties of the equivalent continuum are represented by a set of empirical relationships which express the properties of the jointed medium as a function of joint factor and the properties of the intact rock. Nonlinearity in the finite element analysis has been incorporated using incremental method. The load is increased in a series of steps, or increments. At the beginning of each new increment of loading an appropriate modulus value is selected for each element on the basis of the values of stress in that element. The non-linear stress-strain behaviour is approximated by a series of straight lines. The principal advantages of this procedure are its complete generality and its ability to provide relatively complete description of the load deformation behaviour. Initial stresses may be readily accounted for as tangent modulus is expressed in terms of the stresses only. The principal limitation of this method is that it is not possible to simulate a stress-strain relationship in which stress decreases beyond the peak. To simulate strain softening behaviour one would require to use a negative value of the modulus, and this is not possible in this method of analysis.

During the loading if the element is found to fail in shear, the same is noted, but no changes are effected, and the element is allowed to follow the hyperbolic relation as before, in keeping with the non-linear elastic formulation of the problem. For the elements which fail in tension, the same is assigned very small values of elastic modulus for the subsequent loads. The result obtained by the above analysis have been compared with the experimental results for three different rock materials for both intact and jointed medium. The results have been plotted in the form of stress and strain for each load increment for different values of confining pressures (σ_3) for both intact and jointed specimens with different orientation of joints. Typical results for sandstone and granite are presented in *Figs. 2.3.1* and *2.3.2.* Inclination angle of the joint is the angle between the interface and the direction of major principal stress.

The reliability of the analysis depends upon the joint factor which is a function of the joint orientation, joint frequency and joint strength. So, for a particular jointed medium, by knowing the intact rock properties and by estimating the joint factor, the properties of the jointed rock can be determined. The results are in good agreement even for single and multiple joints and this can be easily extended to materials with very complex joint patterns. The accuracy of the results for a discontinuous system depends on how well the joint factor is estimated for that particular case. Attempts are underway to apply it to real discontinuous systems. Though the

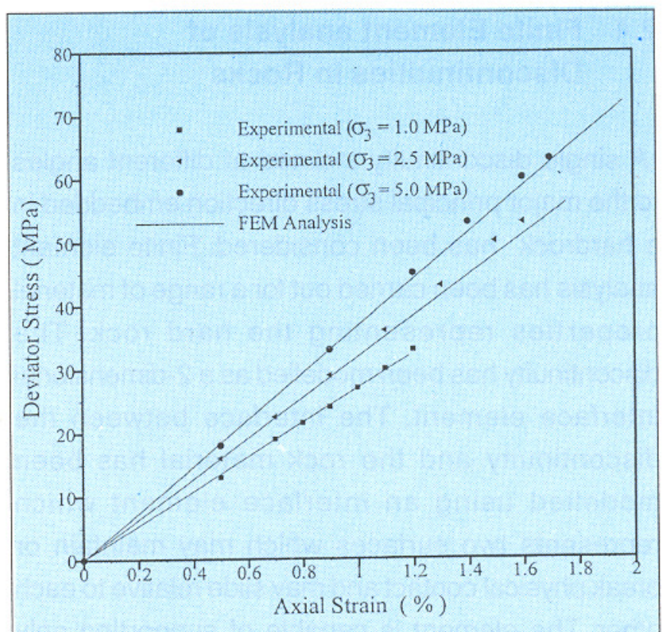

Fig. 2.3.1. Sandstone with joint inclination angle of 60°.

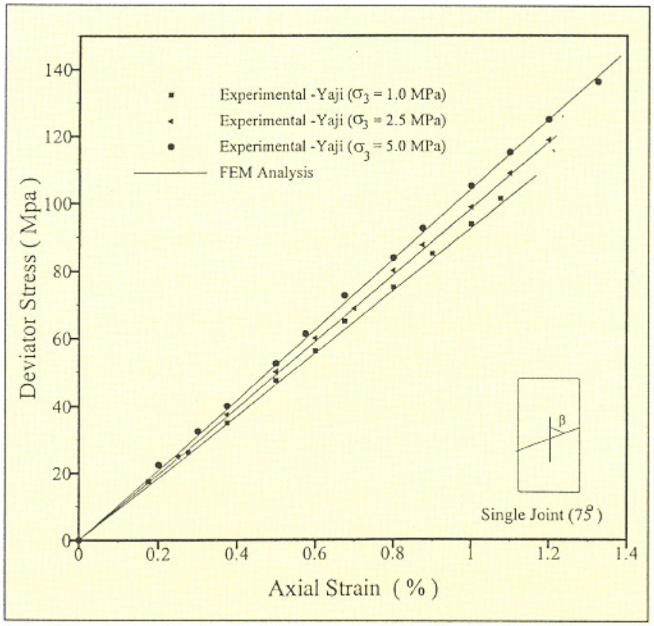

Fig. 2.3.2. Granite with joint inclination angle of 75°.

exponential relationships for average limit are used in the analysis, the expressions for the lower and upper bound are also incorporated in the analysis. Depending on the type of problem and the factor of safety required, any one of the expressions can be chosen and the analysis can be performed.

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2.4 Finite Element analysis of Discontinuities in Rocks

A single discontinuity inclined at different angles to the major principal stress direction embedded in a hardrock has been considered. Finite element analysis has been carried out for a range of material properties representing the hard rock. The discontinuity has been modelled as a 2-dimensional interface element. The interface between the discontinuity and the rock material has been modelled using an interface element which represents two surfaces which may maintain or break physical contact and may slide relative to each other. The element is capable of supporting only compression in the direction normal to the surface and shear (Coulomb friction) in the tangential direction. The element is represented by a pair of coupled non-linear orthogonal springs in normal and tangential directions to the interface and requires an iterative solution for static convergence procedure.

The finite element analysis is carried out for the self weight of the medium and a uniform pressure applied on the two boundaries in x-direction. Both the plane stress and plane strain cases are considered. The stress field and displacement is determined by using the non-linear static analysis. The non-linearity considered in the analysis is a geometric non-linearity introduced by the interface element in the form of boundary non-linearity. All the other elements remain linear elastic throughout the analysis. In the case of geometric non-linearity the classical theory of infinitesimal strains doesn't hold and the strains are obtained from the displacements via a non-linear operator. This type of non-linearity may involve large displacements, large rotations and finite strains. The equilibrium and energy balance equations are written for the deformed configuration of interface elements. For solving these non-linear equilibrium equations, a

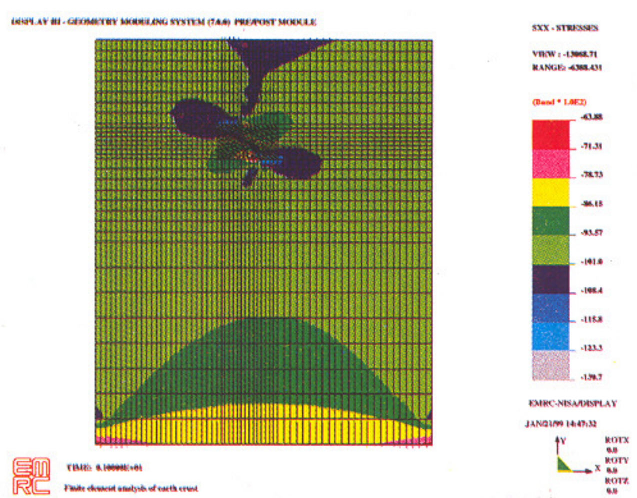

Figure 2.4.1: Finite element analysis of earth crust (Plane strain analysis).

modified Newton-Raphson method is used. The incremental solution is performed in a step by step manner and in each step the iterative scheme is performed until convergence. Since geometric non-linearity is considered, the force convergence criterion is used. The distance of this pressure boundary from the discontinuity is varied to determine the boundary effects. The effect of the pressure boundary on the behaviour of discontinuity has been determined. A typical stress contour is shown in *Fig. 2.4.1*.

(Sridevi Jade and S.S.Nagesha)

2.5 Statistical Modelling of Ash Content in Coal

The linear relationship between specific gravity and ash content for various coal seams in Jharia Coal fields (I, VII-XIII, XV-XVIII) have been derived earlier using the least squares approach. From the estimated parameters for the fitted straight line, the ash content in a particular seam is estimated for a given specific gravity for which the data is already available. It is seen that there are significant departures in the relationship in various seams. This can be said because the error (calculated-observed) behaves differently in different seams. As shown in *Fig. 2.5.1* the error in some seams (XII, XIII, XVI, XVII and XVIII) show similar behaviour than other seams (IX, X and XV). It is remarkably different in seam XI.

In another exercise, the relation between ash content and reciprocal specific gravity was studied. Consider a solid substance in granular form with each of them having a non-uniform size distribution. It is possible that the grains of one substance, when they are mixed, fill up the intergranular spaces of another substance. Such a possibility would arise when their size distribution is different i.e. the average size of one of them would be smaller than that of the other. On the other hand if the mean sizes are comparable, it is fair to suppose that the bulk volume is conserved, when such substances are fixed. Let m_i, v_i and ρ_i be the mass, the bulk

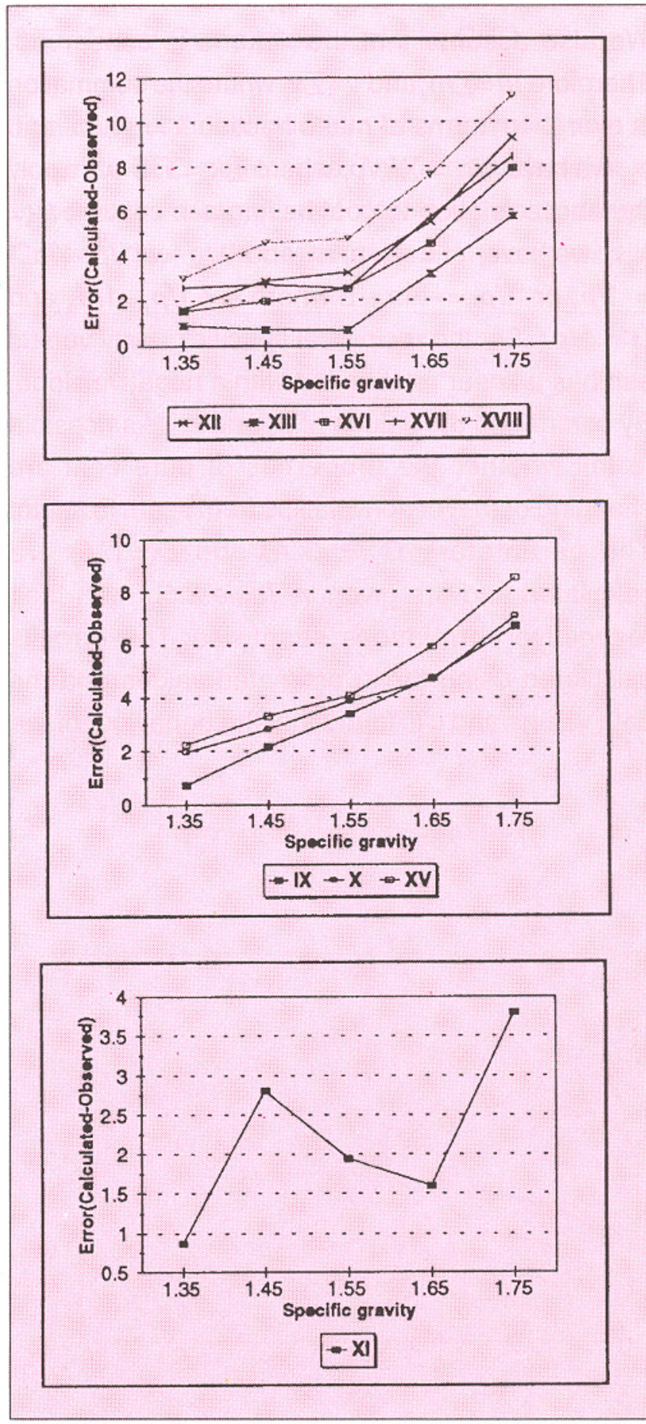

Figure 2.5.1: The estimated error due to the linear relationship of ash content and specific gravity showing different behaviour in various seams.

volume and the specific gravity of each substance ($i = 1,...,n$) and m, v and ρ be the mass, bulk volume and the specific gravity of the mixture. When the pure coal gets mixed with nonvolatile/non-combustible substance (ash), mass is conserved. We also assume that the volume is conserved. Therefore $m = \sum m_i$ and $v = \sum v_i$ where the summation is over i. In terms of mass fraction $k_i = m_i/m$ and ρ_i, we have $1/\rho = \sum k_i/\rho_i$ where $\sum k_i = 1$. If we apply the above relation to coal having ash content a (= k_2), we have $m = (1-a)\,m$ and $1/\rho + a(1/\rho_1 - 1/\rho_2)$ = $1/\rho_1$ or $1/\rho = -Aa + B$ where $A = 1/\rho_1 - 1/\rho_2$ and $B = 1/\rho_1$. So the reciprocal specific gravity versus ash has a linear relation but with a negative slope. By comparing the values of ρ_1 and ρ_2 it is possible to tell whether the properties of pure coal are changing or that of nonvolatiles from seam to seam. The parameters C (= B/A) and D(=$1/A$) are calculated and are given in *Table 2.5.1* with their respective correlations seamwise. The error is calculated using these estimated values and the data values and it is found that the behaviour of the error is similar in the seams as obtained above for the relation between fractional ash and specific gravity.

Table 2.5.1: Linear fit values for the ash and reciprocal specific gravity curve

Jharia Coal Field Seam Number	*C*	*D*	ρ
Zero (No. 1)	1.188	1.461	-0.993
I	1.200	1.494	-0.985
VII	1.551	1.959	-0.995
VIII	1.462	1.796	-0.994
IX	1.499	1.868	-0.993
X	1.453	1.800	-0.990
XI	1.625	2.053	-0.993
XII	1.520	1.899	-0.994
XIII	1.573	1.959	-0.991
XV	1.544	1.952	-0.962
XVI	1.584	1.975	-0.991
XVII	1.762	2.206	-0.992
XVIII	1.569	1.965	-0.986

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