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A STRATEGY FOR HYPOCENTRAL PARAMETER ESTIMATION FOR MICROEARTHQUAKE SURVEYS AT ENGINEERING SITES

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ABSTRACT

The method of least squares should be used to estimate m linearly independent unknown parameters from n observations (m less than n). The problem of estimating four hypocentral parameters (three spatial coordinates of the hypocentre and the time of earthquake occurrence) from P wave arrival times at n (greater than four) stations has the feature that the spatial parameters are linearly dependent on the temporal parameter. By using differences in P wave arrival times at pairs of stations in the array, the earthquake occurrence time can be entirely omitted from consideration, and the method of least squares can be rigorously applied to estimate the spatial coordinates of the hypocentre. The omission of occurrence time does not hamper such objectives of microearthquake surveys at engineering sites as identification of seismically active faults near the sites.

KEY WORDS : Hypocentral Location; Microearthquake Survey; Engineering Site Investigations; Least Squares Analysis.

INTRODUCTION

Microearthquake investigations were first carried out by Oliver and his colleagues in the early nineteen sixties (Oliver et al., 1966). Over the ensuing twenty years or so, they have become a routine feature of site investigations for large engineering projects, such as, dams, nuclear facilities, tunnels, and large underground openings. A review of the recent geotechnical literature pertaining to bridges, highways, land slides, etc. also brings out frequent references to seismic forces, and it would be surprising if, in the near future, project authorities, even in these cases, do not order microearthquake surveys occasionally as parts of their site assessment programmes. We wish to make a few remarks here regarding analysis of microearthquake data for seismicity and seismic risk studies.

An important task in the analysis of data from these surveys is to estimate the hypocentral parameters (latitude, longitude, and depth of hypocentre or focus, as well as occurrence time) of microearthquakes recorded. If P wave arrival times from five or more stations are available for a single earthquake, then its four hypocentral parameters can be estimated, at least in principle, using the

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method of least squares. One forms the error function

$$E(X_H, Y_H, Z_H, T_H) = \sum_{i=1}^{n} (t_{io} - t_{ic})^2 \tag{1}$$

$$t_{ic} = T_H + \tau_{ic}(X_H, Y_H, Z_H, \text{velocity model}). \tag{2}$$

Here X_H, Y_H and Z_H are hypocentral spatial coordinates expressed in a local cartesian rectangular coordinate system, and T_H is the time of earthquake occurrence. t_i is the P wave arrival time at the ith station, subscripts o and c implying observed and calculated values. τ_{ic} is the calculated P wave travel time between the hypocentre and ith station, and is a function of the hypocentral coordinates and the seismic velocity model of the subsurface in the region of the survey. The term P wave is used here as a general title implying first arriving compressional waves, whatever be the path taken by them between the hypocentre and the station. n is the number of stations in the array and must be greater than four.

One estimates the hypocentral parameters by minimizing E with respect to X_H, Y_H, Z_H and T_H and solving the resultant conditional equations. This is in general an iterative procedure. One encounters difficulties at this stage frequently because the iterations do not lead to a converged solution. According to James et al. (1969) the cause of the difficulty lies in the fact that the least squares method should be used to estimate linearly independent parameters, and the three spatial hypocentral parameters are not linearly independent of the time of earthquake occurrence as far as their estimation from a set of P wave arrival times is concerned. The last part of this remark implies to us that if one makes a slight adjustment in the estimates of hypocentral spatial coordinates then one can suitably alter the earthquake occurrence time estimate so that the total squared error E is not affected. James et al. (1969) suggest that the estimation of hypocentral spatial parameters should be delinked from the estimation of eathquake occurrence time. Their iterative procedure comprises of two steps at each iteration, first to estimate earthquake occurrence time for an estimate of the hypocentral location obtained in the preceding iteration using both P and S arrival time data in conjunction with a velocity model, and second to improve hypocentral spatial parameters only by the method of least squares using this estimate of earthquake occurrence time.

PROPOSED METHOD

We have considered the problem of estimating hypocentral spatial parameters using differences in arrival times of P waves at pairs of station. We form the error fnnction

$$E(X_H, Y_H, Z_H) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} [(t_{io} - t_{jo}) - (t_{ic} - t_{jc})]^2$$

which because of (2) becomes

$$E\,(X_H\,,\,Y_H\,,\,Z_H\,) = \sum_{i=1}^{n}\ \sum_{j=i+1}^{n} [(t_{io} - t_{jc}) - (\tau_{ic} - \tau_{jc})]^2 \tag{3}$$

a relation which is entirely free of T_H, the estimate of earthquake occurrence time. The minimization of total square error with respect to X_H, Y_H, and Z_H proceeds in the usual way and yields estimates of the coordinates.

RESULTS

Needless to say that the method has been tested using synthetic data, and as expected in such cases of virtually error free data, the results were very good. For example, in a convenient coordinate system, a hypothetical earthquake was assumed to occur at (—80.00, 130.00, 16.5) in kilometre units Using the calculated P wave arrival times at five nearby points as the observed arrival times and employing the above method, the location of the hypocentre was estimated to be (—80.01, 130.03, 16.53) in kilometre units.

We have also analyzed actual field recorded data using this method. The data pertain to 32 local earthquakes occuring in vicinity of the main central thrust (MCT) in the region between the Yamuna and Bhagirathi valleys of the Garhwal Himalaya (Figure 1) and were obtained during the period of December, 1979, to July, 1980. The same data have been analyzed by Sarkar (1983) using the total squared error function of (1). Sarkar had used a uniform P velocity of 5 km/s for the region but had suggested a value of 5.44 km/s as a better value based on the analysis of other data recorded locally. Accordingly while using the E of (3) we used a contant velocity value of 5.5 km/s.

Before presenting the results we record here the reasons for using a uniform velocity model for the Garhwal Himalayan region. Determination of the detailed velocity structure for this region has not been attempted so far. However 22 of 32 earthquakes whose data have been analyzed were assigned focal depths of less than 5 km below the ground surface locally and none has been assigned a depth greater than 17 km below the ground surface. Also the epicentral distances involved are generally very short, 70 km being the longest. The velocity models proposed by Tandon and Dube (1973), Kamble et al. (1974), Verma (1974), Tandon et al. (1976) for the Himalayan region, although based on observations of seismic waves that have travelled only parts of their paths in the mountains, nevertheless indicate cross-over distances for head waves in excess of 70 km. Hence only direct waves through the granitic layer need be considered by us. The P wave speeds assigned to this layer are 5.48 (Tandon and Dube, 1973), 5.92 (Verma, 1974), 5.72 (Kamble et al., 1974) and 5.65 (Tandon et al., 1976) km/s. In contrast the value of 5.5 km/s used by us has the merit that it is based on analysis of the data from the region of the Himalaya that is of interest to us. Although the rocks exposed in the region are of different types they have been broadly classified by Valdiya (1980) as sedimentary and low grade metamorphic. Their depth extent is unknown. The

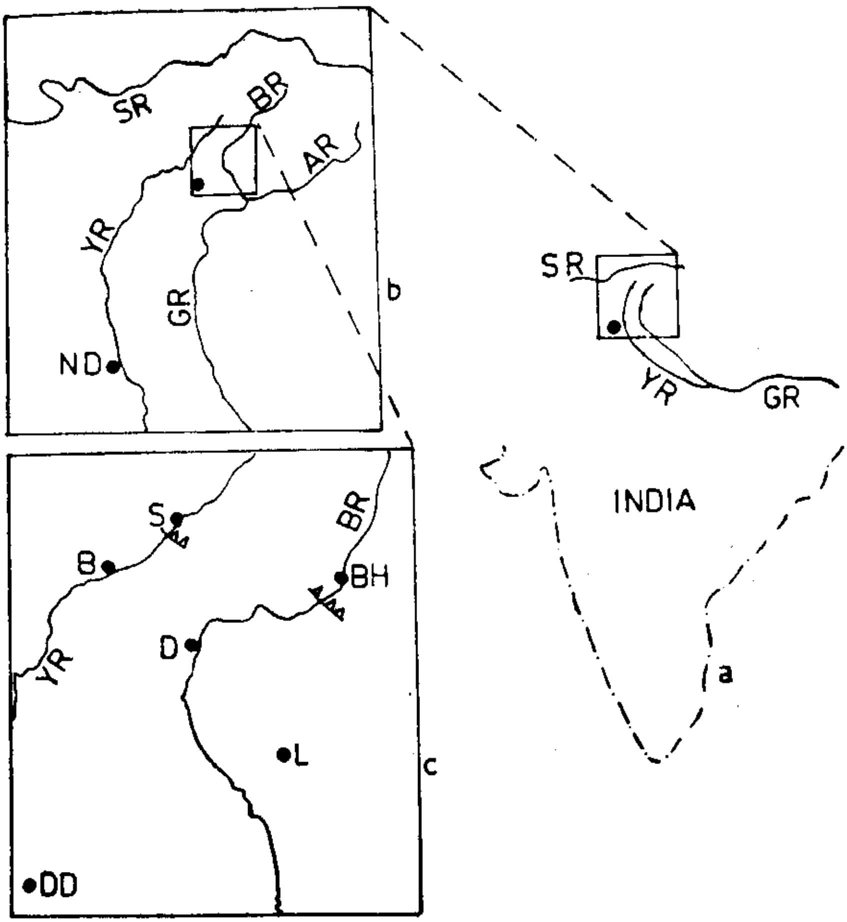

Fig. 1. Maps to indicate the site of the microearthquake survey. Abbreviations for river names are : AK – Alakhnanda river, BR - Bhagirathi river, GR - Ganga river, SR - Satluj river, and YR - Yamuna river. Abbreviations for place names are : B - Barkot, BH - Bhatwari, D - Dunda, DD - Dehra Dun, L - Lambgaon, ND - New Delhi, andS - Sayanachatti. Lines with triangles mark the position of Main Central Thrust in the two river valleys.

uniform model is thus appropriate from this angle also, being the simplest hypothesis in absence of detailed data.

Hypocentral positions estimated by Sarkar (1983) and us are compared in Figures 2 and 3. Shifts in epicentral positions are displayed in Figure 2. The tail of each arrow indicates epicentral position according to Sarkar and the head the position according to us. Figure 3 is a depth section along a vertical plane striking NW-SE. Changes in depth estimates are similarly displayed.

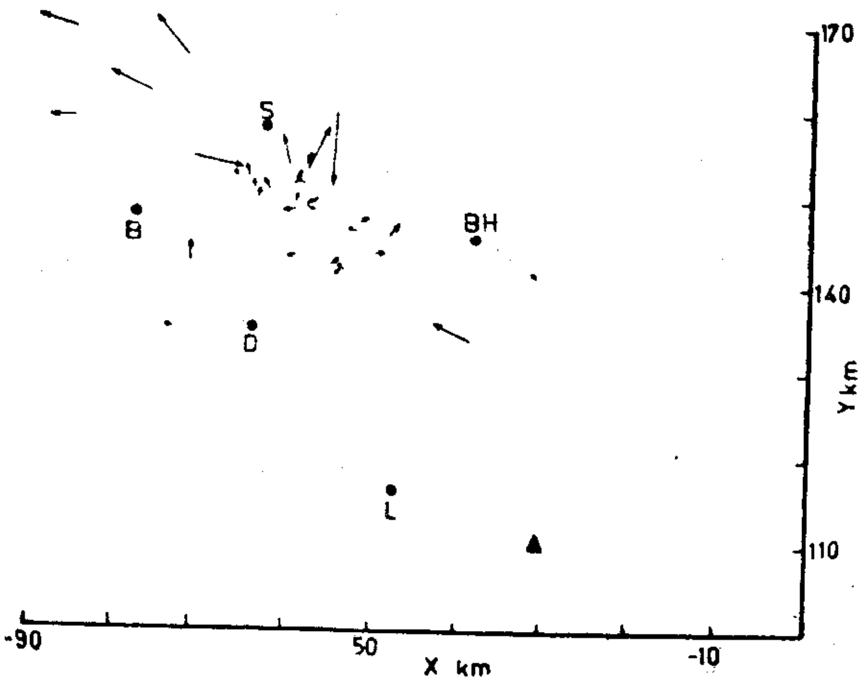

Fig. 2. *Shifts in epicentral locations. Head of an arrow marks the estimated epicentre according to this study and the tail according to Sarkar (1983). The coordinate system has origin at 29.5°N and 79.0°E. Network station locations are shown by labled solid circles. Solid triangle marks the reference point from which distance in the NW direction are measured for the depth sections of Figs 3 to 5.*

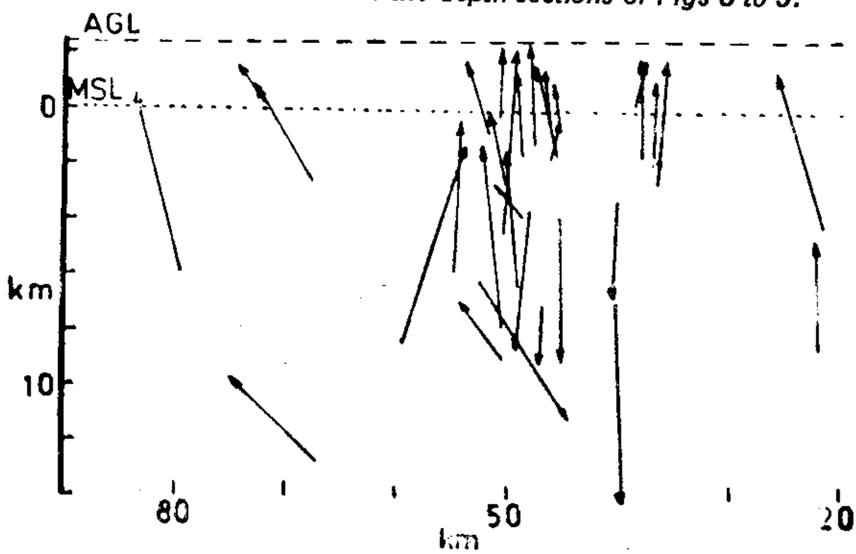

Fig. 3. *Shifts in hypocentral depths. Scheme of representation same as in Fig. 2. Depth section along NW-SE direction. AGL means approximate ground level, shown dashed because of hilly nature of terrain. MSL is mean sea level.*

The differences in hypocentral location estimates cannot be attributed solely to the different velocity values used by Sarkar and us. Sarkar has noted that the effect of using higher velocity in estimating hypocentral parameters is to increase the depth estimates. In other words, if one takes a set of P wave arrival times for a number of stations, and using (1) estimates hypocentral parameters for two P wave velocities, V_1 and V_2 (greater than V_1), then the estimated depths will be greater in the latter case. Since in Figure 3 only six out of 32 arrows are downwardly directed, therefore, the differences in hypocentral location estimates of Sarkar and us cannot be solely due to P velocity differences and must arise in part from the forms of E in (1) and (3).

We have plotted in Figures 4 and 5 the depth sections according to Sarkar and us respectively also. Thus according to Sarkar the earthquakes occurred over a depth range of approximately 2 to 17 km below the local ground surface. However, according to our results (Figure 5) the earthquakes occurred mostly in the depth range of 0-3 km below the ground surface, a few more occurring in the ranges of 3-6 and 9-17 km. No earthquake occurred in the depth range of 6 to 9 km at all.

The above result, although based on few data, is consistent with the view (James Brune, personal communication, 1984) that the seismicity in the Himalaya in the region of the MCT may be occurring at two depth levels: small magnitude, locally recorded events at shallower levels, and larger magnitude, teleseismically recorded events at a deeper level, for which Ni and Barazangi (1984) give depth estimates of 10 to 20 km below MSL.

DISCUSSION

A possible argument against the proposed method could be that time of earthquake occurrence is not determined with it. This is not a critical parameter for many engineering purposes, such as, when the microearthquake survey is carried out to determine the locations of nearest active faults. Even where earthquake occurrence time is required, as when earthquake time series analysis are to be carried out, or return periods of earthquakes are to be estimated, then an average of the T_H estimates based on P wave arrival times and estimated hypocentral location should suffice. An error of one or two seconds here is not going to be critical while estimating return periods of months, years, or decades. Even the earliest P wave arrival time recorded could serve as an estimate of T_H quite well.

The implementation of the new procedure is simpler than the classical procedure based on (1) because 3×3 rather than 4×4 matrices have to be inverted. Also existing computer programs based on (1) can be used with only a few alterations.

Another advantage of the proposed procedure is in that when the method of least squares is used for parameter estimation, then the number of unknowns

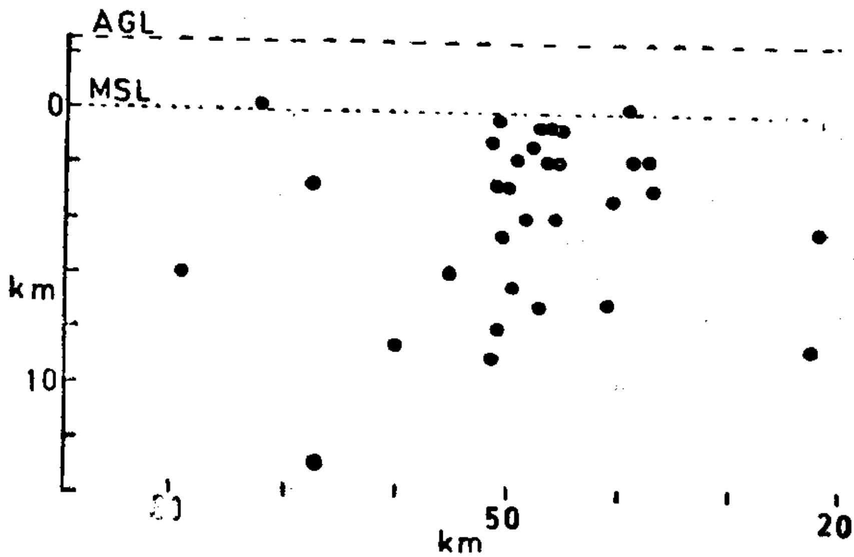

Fig. 4. Depth section of hypocentres according to Sarkar (1983).

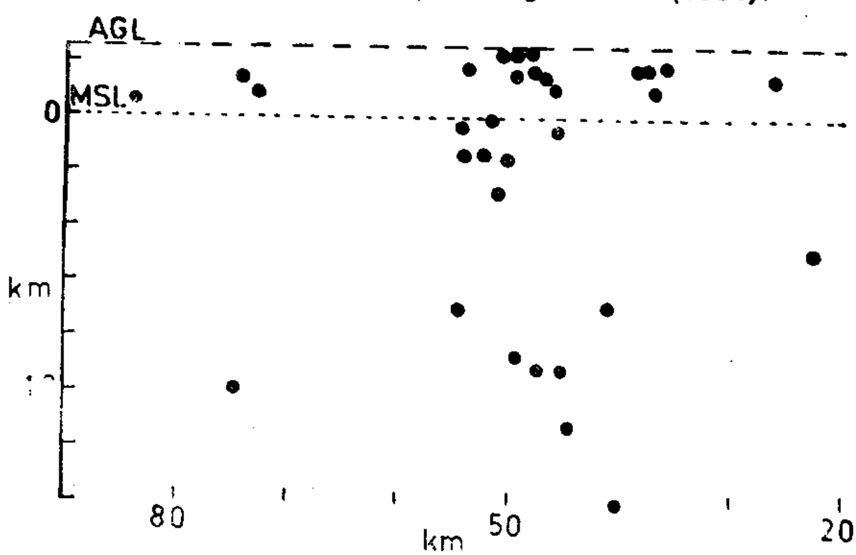

Fig. 5. Depth section of hypocentres according to this study.

should be as small as possible in comparison with the number of observations. Thus estimation of 3 parameters from n P wave arrival times is superior to estimation of 4 parameters, especially when n is between 5 and 8 say. The main advantage, however, remains that only linearly independent parameters are being estimated with the proposed method.

CONCLUSION

A conceptually superior procedure for estimating hypocentral location parameters using the method of least squares has been suggested, and it deserves the attention of engineering seismologists involved with analyses of microearthquake survey data from engineering project sites.

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