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Co-seismic spring flow changes attributed to the March 29, 1999 Chamoli earthquake of Garhwal Himalaya

Irene Sarkar*
Ramesh Chander
Department of Earth Sciences, Indian Institute of Technology, Roorkee, ROORKEE 247 667, Uttaranchal, India

ABSTRACT: The moderate magnitude Chamoli earthquake that occurred on March 29, 1999, in the Garhwal Higher Himalaya produced, among many other observable effects, changes in flow of several artisan springs. Qualitative observations of significant changes in the flow of ten springs located in regions of higher intensity show a strong spatial correlation with our preliminary estimates of perturbing pore pressure field induced in the water saturated shallow rocks of the region by the earthquake in its coseismic phase. The results are significant for it is the first successful attempt in the Himalayan region to investigate the response pattern of the local groundwater flow system to perturbations induced to the ambient tectonic stress regime by a major earthquake.

Key words: Himalayan earthquakes, coseismic phase, hydrologic response, undrained deformation

1. INTRODUCTION

Hydrological response of the earth to large and moderate earthquakes are often manifested through liquefaction of soil, appearance or disappearance of shallow springs and water level changes in wells. Although such earthquake induced changes have been known for more than 2000 years, it is only recently that their implications has been suitably appreciated and highlighted (e.g., Carrigan et al., 1991; Rojstaczer and Wolf, 1992; Muir-Wood and King, 1993; Quilty and Roeloffs, 1997; Manga, 2001). A number of significant case studies e.g., those conducted in California (Rojstaczer, 1988; Rojstaczer and Wolf, 1992; Muir-Wood and King, 1993; Quilty and Roeloffs, 1997; Roeloffs, 1998) and Arakoma Foreland Basin (Ge and Garven, 1992) in USA, in the Canadian Rocky Mountains (Ge and Garven, 1994) and Western Canada (e.g., Garven, 1989) and in Tottori City (Kitagawa and Koizumi, 2000) and Kobe (Tadokoro et al., 2000) in Japan have highlighted the association between active tectonics and groundwater flow and its significance in important geological and geochemical processes, especially within accretionary wedges, subduction zones and along continental margins. These studies highlight the fertility of carrying out similar investigations in other sedimentary basins, subduction zones, continental margins and high ambient tectonic stress regimes of the world.

The Himalaya plate boundary seismic zone appears to be one of the worlds best laboratories to study and analyze how the transient hydraulic and thermal states in the subsurface may evolve in response to changes induced by active tectonic forces within a continent-continent collision zone. This is due to various considerations.

(i) Evidences of significant hydrological changes here due to previous great earthquakes e.g., the 1897 Assam earthquake, 1905 Kangra earthquake, 1934 Bihar–Nepal earthquake and 1950 Assam earthquake, are already documented in literature (Oldham, 1899; Middlemiss, 1910; Dunn et al., 1939; Poddar, 1953). (ii) The region, drained by several major rivers, numerous artisan springs and mountainous streams, is one of the worlds more seismically active zones and the locus of some great intraplate earthquakes. (iii) It has been estimated that presently the Indian plate is underthrusting beneath the Eurasian plate, at a rapid rate of the order of 10 to 20 mm a^{-1}, creating this arcuate belt of intense tectonic activity. Presence of numerous active faults showing repeated Quaternary displacements also indicate that the collision process is ongoing even in recent times. (iv) Finally a major sedimentary basin, composed of terrigenous sediments, low grade metasediments and overthrust sheets of middle and high grade rocks and extending from the Ganga foredeep through the Sub and Lesser Himalaya, is trapped between these two rigid converging lithospheric plate blocks.

Systematic studies of the various forms of tectonically induced hydrologic responses have proved useful in understanding (i) the behavior of crustal rocks under the action of major tectonic forces (e.g., Rojstaczer and Wolf, 1992; Manga, 2001), (ii) the processes that underlie the poroelastic coupling of hydrologic and seismological responses of the earth (e.g., Roeloffs et al., 1989; Quilty and Roeloffs, 1997; Wang, 1997; Roeloffs, 1998; Ge and Stover, 2000) and (iii) also perhaps triggered seismicity (e.g., Hill et al., 1995; Beeler et al., 2000). Since the style of fault displacement and nature of ground vibrations also control earthquake-induced hydrological effects to a considerable extent (Muir-Wood and King, 1993), such studies should also prove helpful in providing observational constraints for reliable estimation of different parameters of the earthquake source model.

In this study, we translate these ideas to the Himalaya

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*Corresponding author: irenefes@iitr.ernet.in

plate boundary seismic zone and investigate the possible hydrological changes that were induced in the shallow subsurface by the most recent hazardous earthquake of the region, the Chamoli earthquake. This moderate magnitude (m_b=6.3, M_S=6.6, M_W=6.4, M_0=5.2×10^{18} Nm) earthquake occurred on March 29, 1999, 05:35 UT, in the higher reaches of the Garhwal segment of the Himalayan tectonic zone. There are differing estimates available for the location of this seismic event. For example, while the US Geological Survey (USGS) located the earthquake hypocentre at 30.51°N, 79.40°E, 15 km, the Indian Meteorological Department (IMD) located it further southeast at 30.30°N, 79.56°E, 18 km. The earthquake induced significant changes to the topography, landscape and groundwater regime of the Alaknanda–Mandakini river valleys and adjoining regions and caused severe damage to human life and property there. A systematic ground and satellite survey of these changes was conducted immediately after the earthquake occurred. The details of that survey have already been documented and reported in literature (Sarkar and Saraf, 2000; Sarkar et al., 2001a; Saraf and Sarkar, 2002).

During this survey, significant changes in the flow of several artisan springs in the region were noted. In this study we analyze the flow in ten such springs where these changes were most spectacular. These ten springs were distributed over approximately 50 km^2 area in the Alaknanda–Birahi Ganga–Mandakini river valleys (Fig. 1), in regions where the earthquake intensity were generally higher. Unfortunately there were no hydrographs available for quantitatively estimating the increase or decrease of discharge of these springs. The survey could provide only qualitative estimates of the changes in springflow induced during the coseismic phase of the earthquake (Fig. 1). In this study we ratiocinate these qualitative estimates and provide constraints for selecting the more plausible model for the causative fault and rupture of the Chamoli main shock. Despite the approximation of analysis adopted, considering the lack of systematically documented studies of the regional ground flow patterns evolving within the compressional tectonics of the Himalaya, we regard our study as significant.

2. THEORY

We address the problem as one of time-dependent flow of interstitial fluid in a porous-elastic solid earth under the action of earthquake related stresses. Biot (1941)'s linearized quasi-static elastic formalism of the response of a fluid saturated porous-elastic medium to a transient load provides us a viable framework for the purpose. This theory discusses the coupling between the pore pressure field and the elastic stress field through constitutive linear relationship between changes induced in pore pressure, mean stress and fluid mass. A major problem due to the coupling terms is that the analytical expressions for the response of a porous elastic media to time-dependent stresses under different realistic boundary conditions can be obtained only after lengthy and involved algebra. It is for this reason primarily that the number of solved stress-related boundary value problems pertaining to porous elastic media is miniscule in comparison to those of the analogous ideal elastic media case. However, for all the solved cases available in literature, there are always two specific limiting responses of a stressed fluid-saturated elastic porous media. These are (i) the instantaneous or undrained response and (ii) the long-time or drained response. It has already been exhibited in literature that, for both these end point responses of a

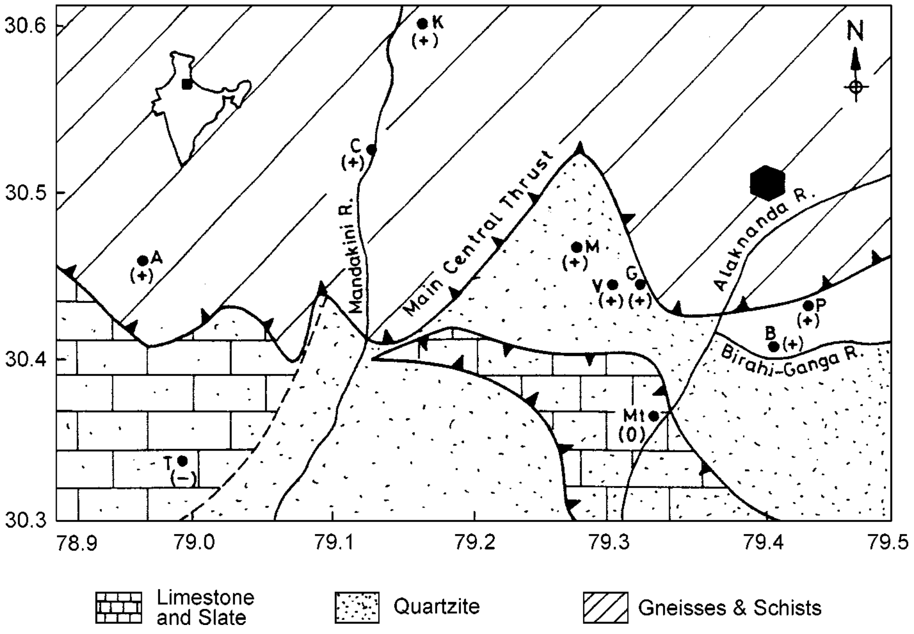

Fig. 1. A map showing the geographic locations of the sites (filled circles) of the springs considered in this article. The abbreviations denote T–Tilwara, A–Agastya Muni, Mt–Maithana, B–Birahi, V–Vairagna, G–Gwar, P–Pipalkoti, M–Mandal, K–Kuonja and C–Chandrapuri. The accompanying plus (+), negative (−) and zero (0) signs identify Chamoli earthquake-induced increased, decreased and unchanged flow at these springs. The solid hexagon marks the US Geological Survey estimated location of the main Chamoli earthquake epicentre. The background geology is after Gansser (1964). The geographic location of this figure is identified in the inset map with a solid dot.

porous elastic media, the results of the corresponding ideal elastic problem can be imported directly (Rice and Cleary, 1976; Detournay and Cheng, 1993).

Our interest in this study is for the undrained response case. This is because the changes in spring flow that we analyze were noted immediately after the earthquake occurred i.e., during the period of short term response of the porous elastic earth to the Chamoli earthquake-induced stresses, when the poroelastic shallow subsurface rocks were undergoing "undrained deformation" (Rice and Cleary, 1976). Undrained deformation of the porous-elastic solid earth implies that the earthquake induced stress changes occurred over a time scale that is too short for the interstitial fluid to migrate from regions of high pressure to regions of low pressure through a process of diffusion. In other words, under such conditions, the diffusive variation of fluid content is zero (Rice and Cleary, 1976; Detournay and Cheng, 1993).

The change in pore pressure (Δp) during the undrained response is called pore pressure change due to compression (Rice and Cleary, 1976). Δp depends on the changes induced in both the mean normal stress and deviatoric stress field (Wang, 1997). It may be estimated from corresponding instantaneous changes $\Delta\sigma_1$, $\Delta\sigma_2$ and $\Delta\sigma_3$ induced in the principal normal stresses using the relation (Wang, 1997),

$$\Delta p = -B[(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)/3 + (3A-1)\Delta\tau^{oct}/\sqrt{2}] \qquad (1)$$

$\Delta\tau^{oct}$ denotes the instantaneous change in the octahedral shear stress field and can be evaluated from $\Delta\sigma_1$, $\Delta\sigma_2$ and $\Delta\sigma_3$ (Jaeger and Cook, 1976, p. 24). A and B refer to Skempton's coefficients and have been experimentally determined for different rock and soil types (Detournay and Cheng, 1993). The sign convention adopted in this equation is that tensile normal stresses are positive.

3. METHOD OF ANALYSIS OF OBSERVATIONS

The following are assumed for the purpose of analysis. (i) The hypocentre of the Chamoli earthquake was at 30.51°N, 79.4°E and 15 km depth, as per the estimates of the US Geological Survey (USGS). (ii) The causative fault has a strike of 282°N, dip of 9°, similar to that of the gently dipping nodal plane of the USGS fault plane solution. (iii) The causative rupture was rectangular in shape, with sides measuring 22.0 km in the fault strike direction and 25.0 km in the fault dip direction. (iv) A uniform slip of 0.4 m occurred over this ruptured area with the hanging wall moving in the up-dip direction during the earthquake process. (v) The earthquake hypocentre was located at the centre of the down-dip edge of the causative fault. (vi) The earth, in the region of interest, is a homogeneous, isotropic, porous-elastic half space with shear modulus (G), undrained Poisson's ratio (ν_u) and Skempton's coefficients A and B having values of 2.3×10^4 MPa (Jaeger, 1969), 0.25 and 0.53 and 0.22 (Detournay and Cheng, 1993; Wang, 1997), respectively.

Regarding our assumptions, the following points may be noted. (i) The choice of the gently dipping nodal plane of USGS as the fault plane is consistent with the plate tectonic model for causative faults of moderate magnitude earthquakes of the Himalayan seismic belt (Seeber and Armbruster, 1981; Ni and Barazangi, 1984; Molnar, 1990). (ii) The assumed values for the rupture dimensions, amount of fault dip and G are consistent with the USGS estimated seismic moment (5.2×10^{18} Nm) of the earthquake (Aki and Richards, 1980). (iii) The assumed values of G, A and B are compatible with experimentally determined values of poroelastic rock type as is generally found in the shallow upper crust in the region of investigation (Detournay and Cheng, 1993; Wang, 1997).

Closed analytical expressions for internal and surficial displacement and strain fields, due to different types of slip mechanisms on finite shear and tensile faults in a homogeneous, isotropic earth medium are easily available in literature (e.g., Mansinha and Smylie, 1971; Okada, 1992). Since the undrained deformation of a poroelastic medium and elastic deformation of a linear isotropic medium are analogous (Rice and Cleary, 1976), we estimated the perturbations to the ambient pore pressure field, induced by the Chamoli earthquake immediately after its occurrence, in the following manner. We used the expression for a dip-slip strain field in a homogeneous, elastic earth medium (Okada, 1992) and generalized Hooke's relation applicable in a Poisson solid to estimate $\Delta\sigma_1$, $\Delta\sigma_2$ and $\Delta\sigma_3$ using the following formulae:

$$\Delta\sigma_i = G(\Sigma\Delta e_i + 2\Delta e_i),\ (i=1,\ 2,\ 3) \qquad (2)$$

Here Δe_1, Δe_2, Δe_3 denote the instantaneous Changes included in the principal normal strains induced by the earthquake. This allowed us to estimate the perturbing (i) mean stress field and (ii) octahedral stress field. The Chamoli earthquake induced perturbing pore pressure field in the region, during the short term of the earthquake process (i.e., Δp) could thus be estimated from the relation of Wang (1997) quoted above.

4. INTERPRETATION OF RESULTS

We exhibit in Figure 2 the spatial variation of Δp on a plane 0.5 km below and parallel to the surface of the porous-elastic half space. In the absence of any information about the depths of aquifers feeding the artisan springs in question, this depth value had to be chosen rather arbitrarily. Also, keeping in mind the quality and quantity of the data to be interpreted, only the regions of increased and decreased pore pressure changes due to compression, identified by plus and minus signs respectively and separated by zero value contours, are shown in the figure.

The projected locations of the ten sites of the springs (Fig. 2) provide information about the possible nature of Δp

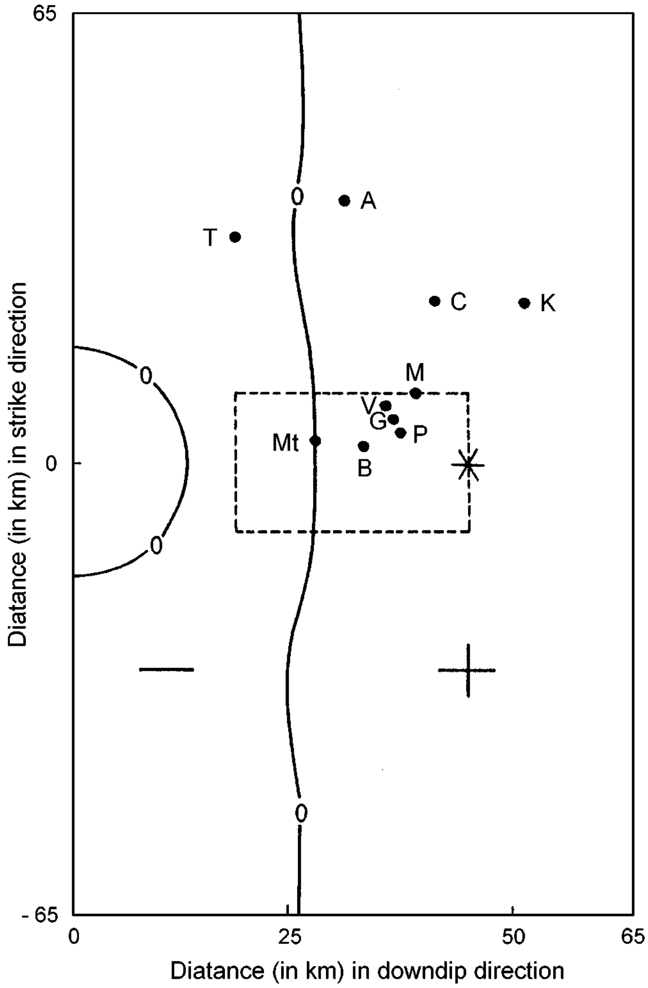

Fig. 2. A map showing the estimated regions where the pore pressure due to compression (see text) may have increased (plus signs) and decreased (minus signs) in response to undrained stress changes induced by the Chamoli earthquake. The pore pressure changes are estimated on a plane 0.5 kilometre below and parallel to the surface of a porous-elastic half space. Only zero value contours (marked with 0s) separating regions of increased and decreased pore pressure on this plane are indicated. The information about the magnitudes of these changes is suppressed in view of the limited, qualitative data considered. The star marks the location of the Chamoli earthquake epicentre as estimated by US Geological Survey. The rectangle marked by dashes represents the projected position of the assumed causative rupture of the earthquake. The filled circles mark the projected positions of the springs as in Fig. 1.

within the poroelastic rocks in the local shallow subsurface. Based on this figure, we predict that, during the coseismic phase of the Chamoli earthquake, due to undrained deformation of the shallow water-infiltrated rocks near Agastya Muni (A), Chandrapuri (C), Kuonja (K), Mandal (M), Viragna (V), Gwar (G), Pipalkoti (P) and Birahi (B), Δp values were significantly increased. A natural consequence of a significant increase in the perturbed pore pressure regime at shallow depths is the squeezing out of interstitial waters from within the porous rocks, thereby increasing the flow of the shallow springs there. This is consistent with our field observations at these sites. In contrast, the estimated decrease in Δp near Tilwara (T) suggest that during this stage, there was inward trasportation of the interstitial waters from the neighbouring shallow rocks, leading to a decrease in flow of the nearby springs; this is in conformity with our observations at Tilwara. No noticeable changes in flow will be expected of springs located near regions where Δp is near zero. For the spring at Maithana, where there was no perceivable change in flow, such an agreement between our observation and prediction is especially striking. This is because this site is located near several other sites where significant increases in spring flows were recorded.

Despite the limited nature of the flow data that is analyzed here, we find an overall consistency between our model-based predictions and field observations. Thus our rationalization of the changes in springflow that were observed during the co-seismic stage of the Chamoli earthquake appears meaningful.

5. DISCUSSION

We acknowledge that there is enough non-uniqueness in the interpretation presented here. This is because of the non-linear involvement of the earth material parameters, viz. G, ν_u, A and B and the earthquake model parameters, viz. location of the earthquake hypocentre, orientation of the causative fault and dimensions, mechanism and amount of slip along the causative rupture, in our analysis. However the following points require to be considered here. Firstly, the average values of G, ν_u, A and B for the water saturated shallow rocks of the Alaknanda, Birahi Ganga, Mandakini river valley and adjoining region may differ by a small measure from those that we have assumed in this study. But such a difference should not affect the general predicted pattern of induced pore pressure change due to compression (Δp) or the proposed rationalization of our field observations. Secondly, as mentioned earlier, the location of the Chamoli earthquake source independently estimated by USGS and IMD are separated by more than 30 km. The estimates of magnitude also differ significantly. We conducted several iterations of our program with both source locations and also with different combinations of the other model parameters. The analysis that we report here (Fig. 2) is based on earthquake model estimated by the USGS. We found that this parameter ensemble was most consistent with our field observations. Thus our procedure of rationalization of observed spring flow changes induced by the Chamoli earthquake might be interpreted as indirect support for the USGS model. We note that detailed analysis of the patterns of induced damage to buildings, topography and hill slopes, observed during the field survey and on the satellite images, also supported the USGS estimated hypocentre location and fault plane solution (Sarkar and Saraf, 2000; Sarkar et al., 2001a; Saraf and Sarkar, 2002).

6. CONCLUDING REMARKS

The status of active tectonics and the ensuing seismic hazard potential of the Himalaya has been studied and assessed through detailed studies by numerous authors (see for example Wadia, 1961; Gansser, 1964; LeFort, 1975; Valdiya, 1980; Seeber and Armbruster, 1981; Ni and Barazangi, 1984; Gaur et al., 1985; Khattri, 1987; Chander, 1988; Khattri et al., 1989; Ni, 1989; Molnar, 1990; Sarkar et al., 1993; Khattri, 1999; Bilham et al., 2001; Sarkar et al., 2001b). In contrast, the transient geohydraulic and geothermal state that is evolving here in response to the prevalent high ambient tectonic stresses, has so far never been systematically or seriously addressed.

The study reported here is one of the few hydrogeologic investigations in the Himalaya. Despite the limited field evidence and highly simplified models of the earth and the earthquake source, we could successfully suggest here the possible changes that were induced on the local ground water regime by the moderate magnitude Chamoli earthquake process in its coseismic phase. Thus our study highlights the immense prospect of regular and systematic monitoring of the discharge of the various rivers, springs and streams and also water level in the shallow wells in the Himalaya. For such an effort can provide deeper and valuable insight into the transient history of the subsurface hydrodynamics and other pre-earthquake changes being induced in the ambient stress field here.

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