CHAPTER – 8

CHARACTERISATION OF KATROL HILL FAULT AS A POTENTIAL SEISMIC SOURCE

The maximum possible magnitude is significantly important input datum for earthquake proof design of large structures. An important clue for achieving this is to estimate the magnitudes of paleo-earthquake events that have occurred along an active fault (McCalpin, 2009) using various parameters like length of surface rupture, displacement and slip rate in available empirical relationships (Schwartz et al., 1984; Wells and Coppersmith, 1994; Anderson et al., 1996; Wesnousky 2008).

The magnitude of an earthquake is an important parameter, which is empirical in nature (Kadirioğlu and Kartal, 2016). Earthquake magnitude can be expressed as an empirical parameter by M_L (local magnitude/ richter magnitude), M_d (duration/ coda magnitude), M_s (surface wave magnitude), m_b/ m_B (body wave magnitude, where m_b refers to the short period and m_B refers to the long period), and M_w (moment magnitude). M_w has been widely used in recent years and is also an instrumental parameter. McCalpin (2009) has emphasized the use of M_w as it is associated with physical parameters of earthquake source fault. Hence, this study takes into account M_w (moment magnitude) for the estimation of paleo-earthquake magnitude along the KHF. There are various approaches for it based on the empirical relationships concerning regression analysis of magnitude and fault parameters of various mapped active faults and such approaches are determined from aftershock sequence studies and that the predicted earthquake size requires an understanding of specific fault characteristics, earthquake return time and the regional tectonic environment (Slemmons, 1982; Wells and Coppersmith, 1994).

CALCULATION OF MOMENT MAGNITUDE (M_w)

Attempts to calculate the maximum earthquake magnitude using the rupture length has been made by various workers such as Wyss (1979), Schwartz et al. (1984), Wells and Coppersmith (1994). Anderson et al. (1996) also included the parameter of fault slip rate along with the associated rupture length. The values of maximum earthquake magnitude calculated using the empirical relationships represent the expected or the average values (Schwartz et al., 1984). To calculate these values Schwartz et al. (1984) used rupture length and slip rate independently in two different regression equations. Whereas, Anderson et al. (1996) claim that the predictions of earthquake magnitudes on active faults were more accurate when the regression for moment magnitude was calculated as a function of surface rupture length (L) along with fault slip rate (S). The regional relationships between earthquake magnitude and rupture length were determined by Acharya (1979) for different parts of the world using the aftershock data of various authors. He found a high correlation between rupture length and magnitude (Acharya, 1979), where scatter in data represented regional differences at constant stress and stress drop. He suggested that these differences were in terms of regional variation in seismic efficiency, which in turn is dependent on the rupture length or magnitude.

In the present study, it has been possible to estimate these parameters with respect to the three Late Quaternary surface faulting events as observed in the Khari river section (Patidar et al., 2008). The slip history diagram (Figure 5.5), in which the displacement observed from the offset across the fault is plotted against time to obtain slip rates corresponding to the different events of surface faulting. The slip rates, displacements and chronology, derived from the Khari river section are mentioned in Table 5.1. The fault parameter of surface rupture length to be used as an input for magnitude estimation was obtained using multiple approaches such as field studies, which documented deformation in the outcrops, the GPR studies, which detected the presence of faulting in Quaternary sediments and microscopic analysis using optical microscope and SEM to observe the grain scale deformation along the fault zone. Based on the evidences of Quaternary deformation using multiple lines of data described above, it is inferred that out of the total ~70 km length of the KHF, at least ~21 km of it in the central part ruptured during the three surface faulting events during the Late Quaternary. The lateral propagation of the surface rupture was not inhibited by the cross fault owing to its smaller scale. The rest of the part of KHF did not rupture as indicated by the absence of Quaternary sediment deformation in the shallow sub-surface and microscopically. During the process of field mapping along the KHF, any causative field evidence like cross fault for the termination of the Late Quaternary surface faulting at either ends could not be found. The large time interval on the scale of thousands of years may be responsible for the loss of evidence to erosion. Alternatively, the surface faulting may have died out at both ends.

The various input parameters as derived in the present study and used for estimation of the magnitude of the Late Quaternary surface faulting events along KHF are shown in Table 5.1. In the present study, an attempt has been made to estimate the moment magnitude (M_w) of the three surface faulting events along the KHF is estimated using the regression equations established by Slemmons (1982), Wells and Coppersmith (1994) and Anderson et al. (1996). These equations are summarized in Table 8.1.

Table 8.1 Empirical relationships used in the present study for calculating magnitude of Late Quaternary surface faulting events using various input parameters.

Input parameters	Formula	References
Surface rupture length (L/SRL) in meters/km	$M_s = 2.021 + 1.142 \log L$	Slemmons (1982)
	$M_w = a + b * \log (SRL)$ *where, a and b are constants with values of 5.08 and 1.16*	Wells and Coppersmith (1994)
Maximum surface displacement (D) in meters	$M_s = 6.793 + 1.306 \log D$	Slemmons (1982)
	$M_w = a + b * \log (MD)$ *where, a and b are regression coefficients with 6.69 and 0.74 values respectively*	Wells and Coppersmith (1994)
Surface rupture length (L) in meters and fault slip rate (S) in mm/year	$M_w = A + B \log L + C \log S$ *where, A, B and C are constants with values of 5.12 $\pm$0.12, 1.16 $\pm$0.07 and 0.20 $\pm$0.04*	Anderson et al. (1996)
M_s to M_w conversion	$M_w = 0.8126 (\pm 0.034602) M_s + 1.1723 (\pm 0.208173)$; for $M_s > 5.5$	Kadirioğlu & Kartal (2016)

Based on length of surface rupture

The length of surface rupture in the present study has been estimated using different techniques, which include the shallow sub-surface investigation of Late Quaternary deposits along the KHF using ground penetrating radar (GPR); while the deformational microtextures in the Late Quaternary samples were examined using optical and scanning electron microscopy (SEM). The GPR results confirmed the propagation of KHF into the Quaternary sediments and the microscopic results testified the seismic deformation observed in them. The extent of KHF lying between south of Bharasar to Ler village appear to have undergone surface faulting, which amounts to ~21km of surface rupture length along the KHF. Therefore, the measure of surface rupture length as 21km is considered in the upcoming calculations for the estimation of moment magnitude (M_w) of paleo-earthquake.

Bonilla and Buchanan (1970) published a report on 68 events of worldwide historical earthquake data, which was later, assembled by Mark and Bonilla (1977) who performed the regression analysis of magnitude over surface fault length. The techniques, their limitations and uncertainties were discussed by Schwartz et al. (1984). For a given rupture length, the empirical relationships between earthquake magnitude and fault rupture length, allow an average magnitude to be selected. Slemmons (1982) assumed that a fraction of total fault length will rupture during an earthquake and devised a relationship between the rupture length and magnitude for a reverse fault as,

$$M_s = 2.021 + 1.142 \log L \qquad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

Where, L is the rupture length in meters.

Substituting the value of L with 21000 mm in Eq (1),

$$\begin{aligned} M_s &= 2.021 + 1.142 * \log (21000) \\ &= 2.021 + (1.142 * 4.322) \\ &= 2.021 + 4.935 \\ M_s &= 6.95 \end{aligned}$$

the final value of M_s as 6.9 is obtained.

The surface wave magnitude (M_s) is converted into moment magnitude (M_w) using the M_s to M_w earthquake magnitude conversion equation of Kadirioğlu and Kartal (2016) as,

$$M_w = 0.8126 (\pm 0.034602)\ M_s + 1.1723 (\pm 0.208173) \qquad . \quad . \qquad (2)$$

Using the above-mentioned conversion equation (Eq. 2), the M_s values of earthquake magnitude obtained is calculated as follows.

$$\begin{aligned} M_w &= 0.8126 (\pm 0.034602)\ 6.95 + 1.1723 (\pm 0.208173) \\ &= 0.8126 * 6.95 \pm (0.034602 * 6.95) + 1.1723 (\pm 0.208173) \\ &= 5.6475 (\pm 0.2404) + 1.1723 (\pm 0.208173) \\ M_w &= 6.81 \pm 0.44 \end{aligned}$$

The final value of moment magnitude (M_w) as 6.8 $\pm$0.44 is acquired after the conversion of M_s values.

Wells and Coppersmith (1994) compiled a worldwide database of source parameters such as fault slip type, M_s, seismic moment, surface and subsurface rupture length, rupture width, rupture area and maximum and average displacement for 421 historical earthquakes, out of which 244 earthquakes with the most accurate parameters were selected to develop an empirical relationship among various source parameters and earthquake magnitude using regression analysis. The regression coefficients were calculated for all-slip-type relationship for both compressional and extensional settings. It was found that there was no difference between the coefficients at a 95% significance level for any relationship. The empirical equation used to calculate the moment magnitude is,

$$M = a + b * \log (SRL) \qquad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

Where, a and b are constants with values 5.08 and 1.16 respectively and SRL is the surface rupture length in kilometres.

$$\begin{aligned} M_w &= 5.08 + 1.16 (\log 21) \\ &= 5.08 + (1.16 * 1.322) \\ &= 5.08 + 1.53 \\ M_w &= 6.61 \end{aligned}$$

The Eq. (3) yielded moment magnitude (M_w) of 6.6 using the fault surface rupture length value of 21 kms.

Based on displacement

The offset Quaternary sediments found on the left bank of the Khari river resulted due to the occurrence of three surface faulting evets during 3.0ka, 28.5ka and 31.8ka (Patidar et al., 2008; Kundu et al., 2010). The displacement such as 2.3mm, 22mm and 3.5mm was estimated during the field survey by measuring the offset distance along the fault displacing the same layer for the three events of surface faulting respectively. The above-mentioned values of displacement for three different evets of surface faulting will be used to estimate paleo-earthquake's moment magnitude (M_w) in the forthcoming calculations.

The values of displacement and slip-rate of the three events of Late Quaternary surface faulting obtained from the Khari river section is shown in Figure 5.3 and Table 5.1. Using the above information and stratigraphic displacement caused by the faulting events, the magnitude of Late Quaternary surface faulting was calculated using a relation given by Slemmons (1982) as

$$M_s = 6.793 + 1.306 \log D \qquad . \quad . \quad . \quad . \quad . \qquad (4)$$

Where, D is maximum surface displacement measured in meters.

Using the above equation (Eq. 3), the magnitude for individual seismic events were calculated. The displacement values of 3.5 m (Event 1), 2.2 m (Event 2) and 2.3 m (Event 3) are substituted in Eq. 3

For 3.5m (Event-1),

$$\begin{aligned} M_s &= 6.793 + 1.306 (\log 3.5) \\ &= 6.793 + (1.306 * 0.544) \\ &= 6.793 + 0.70 \\ M_s &= 7.4 \end{aligned}$$

For 2.2m (Event-2),

$$\begin{aligned} M_s &= 6.793 + 1.306 (\log 2.2) \\ &= 6.793 + (1.306 * 0.342) \\ &= 6.793 + 0.44 \\ M_s &= 7.2 \end{aligned}$$

For 2.3m (Event-3),

$$\begin{aligned} M_s &= 6.793 + 1.306 (\log 2.3) \\ &= 6.793 + (1.306 * 0.361) \\ &= 6.793 + 0.471 \\ M_s &= 7.1 \end{aligned}$$

The substitution of the displacements belonging to three different evets yielded the M_s values 7.4, 7.2 and 7.1 respectively.

The surface wave magnitude (M_s) is converted into moment magnitude (M_w) using the M_s to M_w earthquake magnitude conversion of Kadirioğlu and Kartal (2016) as mentioned in Eq. (2). Using this conversion Eq. (2) and the M_s values of earthquake magnitudes obtained using Eq. (4) are substituted to obtain corresponding Mw values.

For M_s 7.4 (Event-1),

$$\begin{aligned} M_w &= 0.8126 (\pm 0.034602)\, 7.4 + 1.1723 (\pm 0.208173) \\ &= 0.8126 * 7.4 \pm (0.034602 * 7.4) + 1.1723 (\pm 0.208173) \\ &= 6.013 (\pm 0.256) + 1.172 (\pm 0.028173) \\ M_w &= 7.18 \pm 0.45 \end{aligned}$$

For M_s 7.2 (Event-2),

$$M_w = 0.8126 (\pm 0.034602)\, 7.2 + 1.1723 (\pm 0.208173)$$

$= 0.8126 * 7.2 \pm (0.034602 * 7.2) + 1.1723 (\pm 0.208173)$

$= 5.850 (\pm 0.250) + 1.1723 (\pm 0.208173)$

$M_w = 7.02 \pm 0.44$

For M_s 7.1 (Event-2),

$M_w = 0.8126 (\pm 0.034602) 7.1 + 1.1723 (\pm 0.208173)$

$= 0.8126 * 7.1 \pm (0.034602 * 7.1) + 1.1723 (\pm 0.208173)$

$= 5.769 (\pm 0.245) + 1.1723 (\pm 0.208173)$

$M_w = 6.93 \pm 0.44$

The moment magnitude (M_w) 7.1 $\pm$0.45, 7.0 $\pm$0.44 and 6.9 $\pm$0.44 was obtained for the three Late Quaternary surface faulting events along the KHF.

Another empirical relationship formulated by Wells and Coppersmith (1994) involving displacement and moment magnitude (M_w) is,

$$M_w = a + b * \log (MD) \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Where, MD is maximum displacement, a and b are regression coefficients with 6.69 and 0.74 values respectively.

For the displacement values of 3.5m, 2.2m and 2.3m of the three surface faulting events along KHF, the calculation steps of magnitude using the above-mentioned equation (Eq. 5) of Wells and Coppersmith (1994) is as follows.

For 3.5m (Event-1),

$M_w = 6.69 + 0.74 * \log (3.5)$

$= 6.69 + (0.74 * 0.54)$

$= 6.69 + 0.39$

$M_w = 7.08$

For 2.2m (Event-2),

$M_w = 6.69 + 0.74 * \log (2.2)$

$= 6.69 + (0.74 * 0.34)$

$= 6.69 + 0.25$

$M_w = 6.94$

For 2.3m (Event-3),

$M_w = 6.69 + 0.74 * \log (2.3)$

$$= 6.69 + (0.74 * 0.36)$$

$$= 6.69 + 0.26$$

$$M_w = 6.95$$

Therefore, incorporating the values of maximum displacement in equation (Eq. 5) yields M_w 7.08, 6.9 and 6.9 for events 1 (oldest), 2 and 3 (youngest) respectively.

Based on length of surface rupture and slip rate

The slip-rate was obtained by dividing displacement measured in the field by the time interval that elapsed between the two successive events. The slip-history diagram, as described in detail in Chapter – 5 gave a clear idea on the calculation of the slip-rates for the three surface faulting events. 0.09mm/yr is the slip-rate corresponding to the youngest event, which took place at ~3.0ka and 0.66mm/yr corresponds to the penultimate event (PE) that occurred during ~28.5ka. Therefore, the values 0.09mm/yr and 0.66mm/yr will be used along with the estimated surface rupture length of 21km in the upcoming calculations of moment magnitude (M_w) of paleo-earthquake.

M_w was also estimated with the method proposed by Anderson et al. (1996). They used fault slip rate data from 43 earthquake events that occurred in the regions consisting of 15-20 km of seismogenic depth. The estimates such as M_w, surface rupture length (L) and fault slip rate (S) were used and an equation was formulated by regression of moment magnitude (M_w) as a function of fault rupture length (L) and fault slip rate (S) as follows.

$$M_w = A + B \log L + C \log S \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Where, A, B and C in the equation are constants determined by standard least squares regression method possessing the values of 5.12 $\pm$0.12, 1.16 $\pm$0.07 and 0.20 $\pm$0.04 respectively.

Anderson et al. (1996) found that the above equation (Eq. 6) yields more accurate predictions for future earthquake magnitudes estimation as compared to the regressions based solely on fault rupture length (L) as proposed by Well and Coppersmith (1994). The calculation steps for obtaining moment magnitude (M_w) value by substituting the values of surface rupture length (L) as 21 km and slip rate (S) for individual events of Quaternary faulting in equation (Eq. 6) as illustrated below.

For the fault rupture length (L) of 21 km and slip rate of 0.66 mm/yr corresponding to Event-2,

M_w = 5.12 $\pm$0.12 + 1.16 $\pm$0.07 log 21 + 0.20 $\pm$0.04 log 0.66

= 5.12 $\pm$0.12 + (1.16 $\pm$0.07 * 1.322) + (0.20 $\pm$0.04 * -0.180)

= 5.12 $\pm$0.12 + (1.16 * 1.322 $\pm$0.07 * 1.322) + (0.20 * -0.180 $\pm$0.04 * -0.180)

= 5.12 $\pm$0.12 + 1.533 $\pm$0.092 + -0.036 $\pm$0.007

M_w = 6.61 $\pm$0.20

For the fault rupture length (L) of 21 km and slip rate of 0.09 mm/yr corresponding to Event-3,

M_w = 5.12 $\pm$0.12 + 1.16 $\pm$0.07 log 21 + 0.20 $\pm$0.04 log 0.09

= 5.12 $\pm$0.12 + (1.16 $\pm$0.07 * 1.322) + (0.20 $\pm$0.04 * -1.045)

= 5.12 $\pm$0.12 + (1.16 * 1.322 $\pm$0.07 * 1.322) + (0.20 * -1.045 $\pm$0.04 * -1.045)

= 5.12 $\pm$0.12 + 1.533 $\pm$0.092 + -0.209 $\pm$0.041

M_w = 6.44 $\pm$0.17

The empirical relationship provided by Anderson et al. (1996) yielded the M_w values of 6.6 $\pm$0.20 for the PE (Event 2), which took place in early Holocene showing the slip rate of 0.66 mm/year and 6.4 $\pm$0.17 for the youngest MRE (Event 3), which took place in Late Holocene with a slip rate of 0.09 mm/year.

Moment magnitude (M_w) is also calculated in the following paragraph, incorporating the apparent slip rate of 0.25 mm/yr obtained from the slip history diagram (Figure 5.5) and fault rupture length of 21 km in the above formula given by Anderson et al. (1996).

M_w = 5.12 $\pm$0.12 + 1.16 $\pm$0.07 log 21 + 0.20 $\pm$0.04 log 0.25

= 5.12 $\pm$0.12 + (1.16 $\pm$0.07 * 1.322) + (0.20 $\pm$0.04 * -0.602)

= 5.12 $\pm$0.12 + (1.16 * 1.322 $\pm$0.07 * 1.322) + (0.20 * -0.602 $\pm$0.04 * -0.602)

= 5.12 $\pm$0.12 + 1.533 $\pm$0.092 + -0.120 $\pm$0.024

M_w = 6.53 $\pm$0.18

As demonstrated above, the moment magnitude (M_w) for the three Late Quaternary surface faulting events is obtained by including the quantities such as the surface rupture length, displacement and slip rate of the three faulting events in the empirical relationships given by various workers as mentioned in Table 8.1. The Table 8.2 summarizes the M_w values obtained using the above-mentioned fault parameters as inputs (Table 5.1) in various equations (Table 8.1). Although the evaluation of M_w obtained in the present study utilizes different approaches, it is distinctly noticed that all values fall within a narrow range between M_w 6.6 and 7.1.

Table 8.2 Calculated M_w values of the Late Quaternary surface faulting events along the KHF using empirical relationships shown in Table 8.1.

Surface rupturing events	Calculated M_w values				
	Based on surface rupture length		Based on displacement		Based on surface rupture length and slip-rate
	Wells and Coppersmith (1994) (M_w)	M_s values from Slemmons (1982) converted to M_w Kadirioğlu & Kartal (2016)	Wells and Coppersmith (1994) (M_w)	M_s values from Slemmons (1982) converted to M_w Kadirioğlu & Kartal (2016)	Anderson et al. (1996) (M_w)
Event-3			6.9	6.9 ±0.44	6.4 ±0.17
Event-2	6.6	6.8 ±0.44	6.9	7 ±0.44	6.6 ±0.20
Event-1			7.0	7.1 ±0.45	--