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Research Article

EMPIRICAL RELATIONS AMONG THE PARAMETERS ASSOCIATED WITH EARTHQUAKE RUPTURE MECHANISMS FOR IRANIAN EARTHQUAKES

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ABSTRACT

In this study, we aimed to derive the new and more reliable empirical relationships among different seismic parameters associated with the earthquake rupture mechanisms for Iranian earthquakes. For this purpose, we firstly converted the surface wave magnitudes into moment magnitudes in order to prepare a uniform earthquake dataset. Thereafter, we estimated the empirical relationships between moment magnitude and surface rupture length, moment magnitude and maximum displacement, and surface rupture length and maximum displacement. These linear empirical equations were obtained by orthogonal regression and the goodness of fits were discussed in terms of the correlation coefficients. The results obtained by the orthogonal regression in this paper are compared with the results obtained by the least square method in the literature. The present study confirms that representations of statistical correlations among different earthquake faulting parameters can be given more clear and straightforward by the orthogonal regression as compared to the least square method. In addition, such kind of relationships may provide some significant insights for the calculation of the maximum surface rupture length, maximum surface displacement, and associated maximum credible earthquakes for different seismotectonic regions of Iran as well as the estimation of earthquake magnitudes in paleoseismological studies.
Keywords: Iranian earthquakes, orthogonal regression, least square method, correlation coefficient.

1. INTRODUCTION

Iran is located in the active collision zone between the Arabian and Eurasian plates, and it was exposed to major destructive earthquakes in the past. Many strong earthquakes occurred in the instrumental period, especially after the 1970s, and major cities in Iran are mostly located in and around the surrounding of active faults [1]. Iran has a growing economy and a very rapid population growth in the beginning of the 20^{th} century. For this reason, many structures such as highways, dams and high-rise buildings are needed to build. Thus, the definition of rupture characteristics, variability of fault rupture geometry and kinematics, the relationships among these characteristics, and seismic parameters of earthquake faulting may give significant results on the evaluation of fault rupture hazards in Iran [1]. In recent years, a lot of studies have been made to

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evaluate the surface ru pture hazard in Iran, and some empirical relationships have been provided based on the global data [1, 2, 3, 4, 5].

The first detailed quantitative investigation of Iranian earthquakes was made by Nowroozi [4]. A more detailed analysis on the coseismic faulting of Iranian earthquakes including historical and instrumental period was achieved by Berberian [5]. In addition to these studies, Ghassemi [1] used a more complete and update database of Iranian earthquakes in order to define and to analyze the kinematic and geometric properties of surface ruptures. Then, he used the least square method (LSM) and suggested new relationships among several surface rupture parameters. As stated in many studies mentioned above, surface rupture data of earthquakes have been used to estimate the empirical relationships of which are very important for the assessment of rupture hazard and for the estimation of earthquake magnitude based on the length of potential ruptures along active faults [1].

There are a lot of studies on the assessment of different regression models for different data sets of many scientific and engineering fields such as mathematics, physics, statistics, computer science, earth sciences, etc. [1, 2, 4, 6, 7]. One of the most significant problems in these types of applied statistics is to put forth the best approximate regression fitting to the linear equations as a theoretical and practical estimation tool. For this reason, an effective and accurate curve fitting model plays a significant role in the estimation of relationship between a response and an explanatory variable [8]. The emphasis of the regression is both on the model selection and variable selection. Model selection usually focuses on the ability to predict well with less emphasis on getting the variables. Variable selection establishes more emphasis on the estimation of correct variables and is one way to achieve the model selection [9]. A number of curve fitting techniques and mathematical background can be found in the literature in order solve these types of problems. Despite the differences of regression techniques, the basic approach in most of them is the classical optimization theory and the optimization methods. Thus, different regression techniques can be tested to obtain the most suitable physical models and to investigate the validity of these regression models.

In this study, we tried to estimate the most approximate relations among different faulting parameters for Iranian earthquakes. Although several techniques as stated in literature, we did not apply these models since these types of techniques have been used for more certain fields and they have not been used in geophysical applications. In this context, a comparison between LSM and orthogonal regression (OR) techniques was made in order to obtain the optimal statistical solutions between different variables. For this purpose, we first obtained a uniform database considering the magnitude scales between the moment magnitude (Mw) and surface wave magnitude (Ms) for Iranian earthquakes. Then, we tried to estimate the empirical relationships among the different earthquake faulting parameters such as Mw and surface rupture length (SRL), Mw and maximum displacement (MD), and SRL and MD. OR fitting [10] is preferred in the estimation of relationships between mentioned parameters since the standard LSM is based on the assumption that horizontal axis values are estimated without error [10]. Thus, the main purpose of this study is to drive the most up-to-date and suitable relationships among the faulting parameters for a reliable fault rupture hazards of Iran. Moreover, as stated in literature studies [1, 3, 4, 5], these types of empirical relationships may be used in the estimation of the maximum surface rupture length, maximum surface displacement, and associated maximum credible earthquakes for different parts of Iran.

2. METHOD AND DATABASE

2.1. Brief Description of Linear Regression Problem and Orthogonal Regression

The linear regression problems have a natural relationship to distances in Euclidean geometry, and the solutions can be done empirically by using the tools of linear algebra. In order to apply a linear regression to the data, several distance functions or metrics can be used. In fact, the linear regression problem is categorized under the class of mathematical problems and it is one of the most important data analysis tools [7]. To formulate the linear regression model, it is presumed that there are *n* measurements or observations on the dependent variable y, and some number $p \geq 1$ of independent variables $x_1, \ldots, x_p$ of each one for which it is known *n* values as well. Giloni et al., [11] defined the formulation as follow:

$$\mathrm{y} = \begin{pmatrix} y_1 \\ . \\ . \\ . \\ y_n \end{pmatrix} \cdot \mathrm{X} = \begin{pmatrix} x_1^1 & . & . & . & x_p^1 \\ . & & & & . \\ . & & & & . \\ . & & & & . \\ x_1^n & . & . & . & x_p^n \end{pmatrix} = \begin{pmatrix} \mathrm{x}^1 \\ \\ \\ \\ \mathrm{x}^n \end{pmatrix} = (\mathrm{x}_1, \ldots, \mathrm{x}_p) \tag{1}$$

where $y \in R$ is a vector of *n* observations and X is $n \times p$ matrix of real frequently referred to as the design matrix. Furthermore, $\mathrm{x}_1, \ldots, \mathrm{x}_p$ are column vectors with *n* components and $\mathrm{x}^1, \ldots, \mathrm{x}^n$ are row vectors with *p* components corresponding to the columns and rows of X, respectively. The hypothesized linear regression model can be written as [7]:

$$\mathrm{y} = \mathrm{X}\beta + \varepsilon \tag{2}$$

where $\beta^T = (\beta_1, \ldots\ldots, \beta_p)$ is the vector of parameters of the linear model and $\varepsilon^T = (\varepsilon_1, \ldots\ldots, \varepsilon_n)$ is a vector of *n* random variables corresponding to the error terms in the asserted relationship. An upper index *T* denotes "transpose" of a vector or matrix. In the statistical model, the dependent variable y, thus, is a random variable for which we obtain measurements or observations that contain some "noise" or measurement errors that are captured in the error terms ε. However, for the numerical problem that we are facing, it is stated as follow [7]:

$$\mathrm{y} = \mathrm{X}\beta + r \tag{3}$$

where given some arbitrarily fixed parameter vector β, the components r_i of the vector $r^T = (r_1, \ldots, r_n)$ are the residuals that result, given the observations y, a fixed design matrix X, and the chosen vector $\beta \in R^p$. Thus, the residuals, *r*, are in terms of the statistical model, realizations of the random error terms ε given the particular observations y and parameter settings β. Given y and X, the general objective in linear regression is to find parameter settings $\beta \in R^p$ such that some appropriate measure of the dispersion of the resulting residuals $r \in R^n$ is as small as possible [12].

Giloni and Padberg [12] stated that it has a possibility that, e.g., $x_1^j = 1$, for all $j \in \{1, \ldots, n\}$ in the design matrix X. In this situation, it is referred to β_1 as the "intercept term" corresponding to the situation in the two parameter case, i.e., when p=2. If $x_1^j = 1,$ for all $j \in \{1, \ldots, n\}$ and p=1, the problem of finding a "best" fitting scalar β_1 means that we want some good measure of "centrality" of the observations y.

Total least square or orthogonal regression is one of the most widely known techniques for errors-in-variables estimation in the simple linear regression model. It is also sometimes named as the functional maximum likelihood estimator under the constraint of known error variance ratio. In the standard linear regression methods, the main purpose is to minimize the sum of the squared vertical distances between the *y* data values and the corresponding y values on the fitted line while the main purpose in OR is to minimize the perpendicular (orthogonal) distances from the data points to the fitted line. This well-known estimator is an old method and performed in some studies [e.g., 13, 10, 14]. The use of OR must include a careful assessment of equation error, and not merely the usual estimation of the ratio of measurement error variance. When its assumptions hold, OR is a perfectly justifiable estimation model. However, it often lends itself to misuse by the unwary as a method, because OR does not consider the equation error [7].

2.2. Correlation Coefficient and Goodness of Regression Fit

The selection of the best probability distribution for a dataset is one of the most significant problem in regression analyses. As stated in many studies in literature, different distributions can be used and the best fitting regression can be preferred. However, there has not been a certain rule in the selection of the most suitable distribution. In most cases, the selection of a suitable distribution is based on goodness of fit assessment. The goodness-of-fit technique can be described as the method for examining how well sample data agree with an assumed probability distribution as its population. Selection criteria among the goodness-of-fit tests, the determination of correlation coefficient (R^2) has been known as a powerful and conceptually simple method. Although the R^2 is solely based on the covariance penalty, it plays an important role in model fit assessment and can give an acceptable and rapid solution [15].

The R^2 is generally given as the quantity that estimates the percentage of variance of the response variable explained by linear relationship with the explanatory variables. Correlation coefficient can be estimated by means of the ratio [7]:

$$R^2 = \frac{ESS}{TSS} = 1 - \frac{RSS}{TSS} = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \tag{4}$$

where *ESS*, *TSS* and *RSS* are the explained, total and residual sum of squares, respectively. When there is an intercept term in the linear model, this determination of correlation coefficient is actually equal to the square of the correlation coefficient between y_i and $\hat{y}_i$:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2 \sum_{i=1}^{n}(\hat{y}_i - \bar{\hat{y}})^2}} \right)^2 \tag{5}$$

where $\bar{y}$ and $\bar{\hat{y}}$ indicate the mean values of the observations y_i and the fitted quantiles $\hat{y}_i$, respectively. Equation (5) has a proper interpretation in that R^2 measures the goodness of fit of the regression model by its ability to predict the response variable, ability measured by the correlation. The correlation coefficient is location and scale invariant and essentially measures the linearity of the probability plot, supplying a quantitative assessment of fit. As a result, it is assumed that the observations could have been drawn from the fitted distribution if the value of R^2 is close to 1.0 [15].

2.3. Database

The database used in this study is compiled form Ghassemi [1] in which 46 Iranian earthquakes between 1900 and 2012 were used for the analyses (Table 1). Ghassemi [1] used a catalog of Iranian earthquakes related to direct loses as a preliminary basis and the preliminary dataset was reduced to 41 events. Then, 5 more earthquakes were also added to complete the dataset and to extend it to 2012. This dataset is not complete for SRL and MD, therefore the results in this study may differ from specific earthquakes which are used to estimate the relationships between Mw and SRL, Mw and MD, and SRL and MD. For the statistical analyses, Mw scale was preferred in order to obtain a uniform database since the available reported magnitude type is Mw for more recent Iranian earthquakes. For this reason, it was necessary to convert the reported Ms into Mw in order to estimate a relationship between two magnitude scales. The catalog consists of 166 earthquakes for Mw and Ms between 1962 and 2004, which were compared with reported Mw in different catalog such as ISC (International Seismological Centre), NEIC (National Earthquake Information Service), USCGS (United States Coast and Geodetic Survey), etc. [1]. In order to have a uniform catalog for Iranian earthquakes, a relationship between Ms and Mw is firstly formulated for older events which has not Mw scale before 1976 and then, the other empirical relationships of faulting parameters are estimated (One can find many details for the database of Iranian earthquakes in Ghassemi [1]).

3. RESULT AND DISCUSSIONS

In this study, new empirical relationships between the seismic parameters of the faults (mostly magnitude) and different rupture characteristics are estimated to evaluate the fault rupture hazards in Iran. Using the OR fit and based on the surface ruptures of Iranian earthquakes, empirical relationships are suggested for Mw and Ms, Mw and SRL, MD and Mw, and MD and SRL for strike-slip and thrust or reverse faults. Ghassemi [1] used LSM and suggested some empirical relationships among Mw, MD and SRL associated with different earthquake rupture mechanisms in Iran. Table 2 shows the comparison between the results of Ghassemi [1] and this study. Also, all statistical relationships estimated in this study with OR are shown in Figure 1 with their confidence intervals. Regression analyses have been used by researches in different disciplines to estimate the mathematical model for measured dataset. Linear LSM cannot make a good estimate with the abnormal error distribution [7]. A more accurate and better characterization of the solution of a problem is made by minimizing the sum of residual error magnitude. In this context, correlation coefficients of the regression fits can be used as a reliable and reasonable tool in comparison of the results. As shown in Table 2 and Figure 1, OR fits give stronger correlation coefficients than LSM in many estimations expect a few ones.

Table 1. Details of faulting parameters for Iranian earthquakes between 1900 and 2012 (see Ghassemi, [1] for details). RSS: right lateral strike-slip, LSS: left lateral strike-slip, N: normal, T: thrust or reverse, v: vertical component of displacement, h: horizontal component of displacement

No	Date	Longitude	Latitude	Rupture Mechanism	Mw	SRL	MD
1	23.01.1909	49.13	33.41	RSS-N	7.3	>40	>1
2	18.04.1911	57.03	31.23	T	6.3	18	v. >0.5
3	01.05.1929	57.81	37.73	RSS	7.2	74	2
4	06.05.1930	44.60	38.24	N-RSS	7.1	16-30	4
5	16.02.1941	58.87	33.41	RSS	6.3	8-10	0.5-1
6	27.11.1945	63.47	25.02	T	7.8		
7	23.09.1947	58.67	33.67	RSS	6.8	20	v. 0.3-0.8 h. 1
8	05.07.1948	57.73	29.88	RSS	6.1		
9	05.10.1948	58.55	37.88	RSS	7.1		
10	12.02.1953	54.88	35.39	T	6.5	>8	v. >1.4
11	02.07.1957	52.47	36.07	T	6.8		
12	13.12.1957	47.82	34.58	T	6.7		
13	16.08.1958	48.17	34.30	N-RSS	6.7	20	v. 1.5
14	01.09.1962	49.81	35.71	T	7.1	80	v. 1.4 h. 0.6
15	31.08.1968	58.96	34.02	LSS	7.1	80	v. 2.1 h. 4.5
16	01.09.1968	58.23	34.05	T	6.4		
17	30.07.1970	55.89	37.67	RSS	6.5		
18	10.04.1972	52.98	28.38	T	6.9		
19	02.07.1972	50.85	30.06	T	5.5	1.5	v. 4
20	24.11.1976	44.02	39.12	RSS	7.1	55	v. 0.5 h. 3.5
21	21.03.1977	56.45	27.59	T	7.0		
22	06.04.1977	50.76	31.90	T	5.9		
23	19.12.1977	56.61	30.90	RSS	5.8	19.5	h. 0.2
24	16.09.1978	57.12	33.40	T	7.3	85	< 1.7
25	16.01.1970	59.50	33.80	LSS	6.5		
26	14.11.1979	59.81	33.91	RSS	6.6	20	1
27	27.11.1979	59.63	34.05	LSS	7.1	68	2.5-4
28	11.06.1981	57.68	29.85	RSS-T	6.6	15	
29	28.07.1981	57.77	29.97	T	7.0	65	0.4
30	20.11.1989	57.72	29.90	RSS	5.8	11	v. 0.01 h. 0.004
31	20.06.1990	49.23	37.00	LSS	7.3	>80	v. 0.95 h. 0.6
32	06.11.1990	55.46	28.24	T	6.4	15	v. 1.5
33	23.02.1994	60.54	30.78	T	6.1	9.5	1.7
34	24.02.1994	60.51	30.79	T	6.2		
35	04.02.1997	57.31	37.73	RSS	6.4	15	0.5-1.0
36	28.02.1997	48.07	38.12	RSS	6.0		
37	10.05.1997	59.81	33.85	RSS	7.2	125	v. 0.9 h. 2.3
38	14.03.1998	57.59	30.14	RSS-N	6.6	23	h. 3
39	18.11.1998	57.58	30.33	RSS	5.3	4	
40	22.06.2002	49.01	35.62	T	6.4	3	0.16
41	26.12.2003	58.27	28.90	RSS	6.5	5	0.2
42	28.05.2004	51.57	36.29	T	6.2		
43	22.02.2005	56.79	30.71	T	6.4	13	1
44	27.11.2005	55.83	26.75	T	6.0		
45	20.12.2010	59.19	28.33	RSS	6.5	14	0.05
46	11.08.2012	46.78	38.41	RSS	6.4	13	0.5-1

Although we calculated some weak correlation coefficients such as R^2=0.299 and R^2=0.411, they are proposed in the estimation of earthquake hazard in Iran, because as stated by Ghassemi [1], these estimations are based upon the analyses over earthquakes that occurred in Iran and they clearly indicate the potential ranges of changeability of earthquake faulting parameters. They may also give an insight to extreme limits in rupture hazard assessments and these empirical relationships may supply useful information for paleoseismological researches on active faults of the Iranian Plateau [1]. Since this study does not aim to evaluate and discuss the earthquake fault rupture hazards in Iran, we did not make a detailed discussion on this subject. One can find many details in Ghassemi [1] for the insights of earthquake surface rupture hazards.

Table 2. A Comparison between the results of Ghassemi [1] and this study

Ghassemi [1] with LSM	**This study with OR**	**Fault type**
Mw=1.020+0.848Ms (R^2=0.852)	Mw=0.668+0.913Ms (R^2=0.986)	All
Mw=5.294+0.966Log(SRL) (R^2=0.873)	Mw=5.570+0.822Log(SRL) (R^2=0.945)	T
Mw=5.568+0.806Log(SRL) (R^2=0.797)	Mw=4.630+1.489Log(SRL) (R^2=0.788)	SS
Mw=5.523+0.870Log(SRL) (R^2=0.800)	Mw=4.972+1.248Log(SRL) (R^2=0.778)	All
Log(MD)=-2.230+0.320Mw (R^2=0.114)	Log(MD)=-3.002+0.419Mw (R^2=0.299)	T
Log(MD)=-7.435+1.105Mw (R^2=0.658)	Log(MD)=-6.545+0.927Mw (R^2=0.779)	SS
Log(MD)=-6.320+0.938Mw (R^2=0.532)	Log(MD)=-6.123+0.870Mw (R^2=0.650)	All
Log(MD)=-0.559+0.352Log(SRL) (R^2=0.240)	Log(MD)=-0.630+0.421Log(SRL) (R^2=0.411)	T
Log(MD)=-0.927+0.751Log(SRL) (R^2=0.616)	Log(MD)=-1.909+1.287Log(SRL) (R^2=0.697)	SS
Log(MD)=-0.778+0.609Log(SRL) (R^2=0.457)	Log(MD)=-1.461+1.001Log(SRL) (R^2=0.588)	All

As shown in Table 2 and Figure 1, strong positive R^2 expect a few ones are found with the OR fits. R^2 of all relations for Iranian earthquakes changes between 0.299 and 0.986. A reason of poor correlation coefficients may be resulted from the small size of the data as seen in Figures 1e and 1h. When compared the results of OR with LSM, it can be say that linearity of the probability method is measured by providing a quantitative assessment of the fits. For all relations with fit curves, corresponding equation and 95% confidence intervals are also given in all Figures. Also, the number of events for 95% confidence limit of all regressions are computed as 35 events in Mw-Ms relation for all earthquake mechanisms, 6 events in Mw-SRL relation for thrust and reverse faults, 11 events in Mw-SRL relation for strike-slip faults, 17 events in Mw-SRL relation for all fault mechanisms, 6 events in MD-Mw relation for thrust and reverse faults, 12 events in MD-Mw relation for strike-slip faults, 12 events in MD-Mw relation for all fault mechanisms, 6 events in MD-SRL relation for thrust and reverse faults, 11 events in MD-SRL relation for strike-slip faults, 11 events in MD-SRL relation for all fault mechanisms.

It is well known that earthquake faulting parameters are highly related to earthquake magnitude as well as the geological or tectonic structure of the region. With the obtained relations among the faulting parameters of Iranian earthquake, we can estimate an expected value for a dependent parameter from a measured independent parameter. The suggested empirical relations in this study can be used in order to estimate the other variables such as maximum surface rupture length, maximum surface displacement, and associated maximum credible earthquakes for different parts of Iran. It means that the presented regressions in this study can be appropriate for estimating of desired faulting parameters along the related fault segments and can be useful for engineering estimation purposes [7]. As a result, a brief and general comparison is made between the results by OR method of this study and the results by LSM of Ghassemi [1]. The results show that empirical equations estimated by OR can be thought as more suitable and more reliable for Iranian earthquakes.

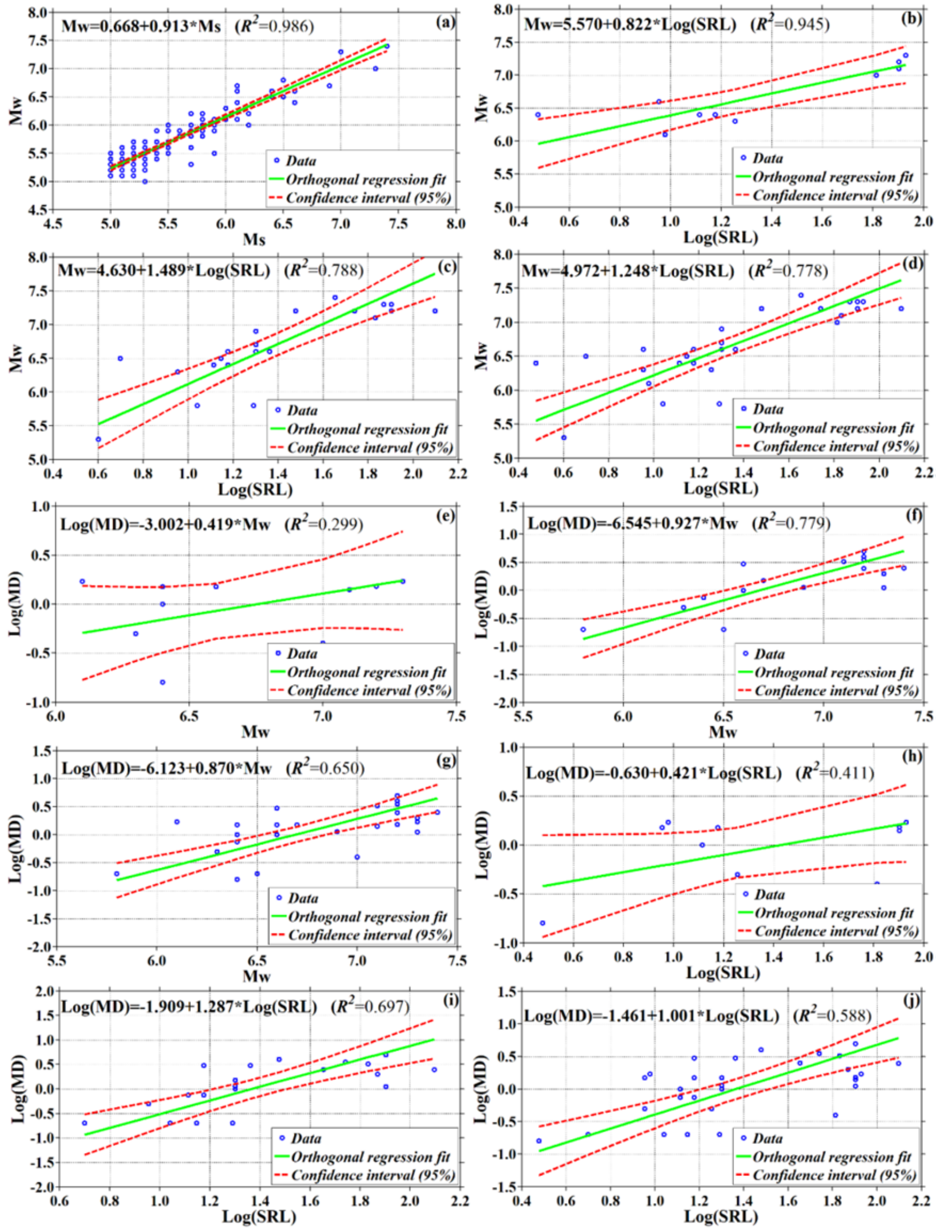

Figure 1. Empirical relationships with OR method between (a) Mw and Ms for all earthquake mechanisms, (b) Mw and SRL for thrust faults, (c) Mw and SRL for strike-slip faults, (d) Mw and SRL for all fault mechanisms, (e) MD and Mw for thrust faults, (f) MD and Mw for strike slip-faults, (g) MD and Mw for all fault mechanisms, (h) MD and SRL for thrust faults, (i) MD and SRL for strike-slip faults, and (j) MD and SRL for all fault mechanisms.

4. CONCLUSIONS

This study focuses on the estimation of relationships among different seismic parameters of earthquake rupture mechanisms in Iran. We firstly obtained a relationship between moment magnitude and surface wave magnitude. Then, we tried to drive the best fits between moment magnitude and surface rupture length, moment magnitude and maximum displacement, and surface rupture length and maximum displacement. Orthogonal regression fitting is used for all the linear relationships and correlation coefficients of the curve fittings are preferred as a robust and practicable tool in comparison with the results in literature. The results show that the representations of empirical relationships among different faulting parameters will be made as more up-to-date and more trustworthy by orthogonal regression fit rather than traditional least square method. Regional variations of different parameters in all statistical relations can be interpreted in terms of local differences in geological and tectonic structures. Empirical relations in this study suggest that regional seismic and tectonic framework is dependent on magnitude, rupture length or displacement. The derived equations may also give useful outcomes in the computation of earthquake magnitudes in paleoseismological researches and may be used to estimate the extreme limits of rupture hazard evaluations in Iran.

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