

A probabilistic prediction of the next strong earthquake in the Acapulco-San Marcos segment, Mexico

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RESUMEN

El uso de las probabilidades condicionales de recurrencia representa una manera válida y razonable de estimar la posible ocurrencia de grandes sismos. En este trabajo suponemos la distribución gama y logarítmico normal para los intervalos de recurrencia de los temblores. El proceso sísmico en el segmento de Acapulco-San Marcos puede modelarse como un proceso de renovación usando un catálogo de grandes sismos ($M_s \geq 7$). Para el modelo gama, un sismo grande puede ocurrir antes de agosto de 2016 \pm 5.14 años. Para el modelo logarítmico normal un sismo grande podrá ocurrir antes de julio de 2016 \pm 5.15 años.

PALABRAS CLAVE: Sismos, predicción probabilística, densidad condicional, distribución gama, distribución logarítmico normal, tiempo de recurrencia, error de predicción.

ABSTRACT

Conditional probabilities for recurrence times of large earthquakes are a reasonable and valid form for estimating the likelihood of future large earthquakes. In this study we assume a gamma and a lognormal distribution for the recurrence time intervals of large earthquakes. The seismic process in the Acapulco-San Marcos fault-segment can be modelled as a renewal process, using a list of historical strong earthquakes ($M_s \geq 7$). For the gamma model, a highly damaging earthquake ($M_s \geq 7$) may occur approximately before August 2016 \pm 5.14 (yrs). For the lognormal model, a highly damaging strong earthquake ($M_s \geq 7$) may occur approximately before July 2016 \pm 5.15 (yrs).

KEY WORDS: Earthquakes, probabilistic prediction, conditional density, gamma distribution, lognormal distribution, recurrence time, prediction error.

INTRODUCTION

Mexico City lies over 200 miles (320 km) from the subduction zone of the Cocos and North America plates. The 19 September 1985, Michoacán, Mexico, earthquake ($M=8.1$), claimed 10 000 lives and left an estimated 250 000 homeless (Astiz *et al.*, 1987).

Sykes *et al.* (1999) proposes 10 or 30 years as warning time for long-term predictions with average repeat time and statistical variations in individual repeat times for a fault-segment, and the time elapsed since the previous earthquake occurred. The physical basis is the slow build up of stress.

In Mexico a 30-year prediction time is appropriate for active fault-segments of the Mexican subduction zone, extending over a length of about 1000 km along the Middle America trench from Jalisco-Colima to Oaxaca region.

By combining data from many different faults, Nishenko and Buland (1987) obtained a reasonably good fit of a lognormal distribution to recurrence times. McNally and Minster (1981) have argued that a Weibull distribution is appropriate. Other stochastic models have been used for

seismic hazard evaluation, the most common hazard model being the Poisson process (Cornell, 1968).

The Working Group on California Earthquake Probabilities (1988) produced a conditional probability map for the San Andreas fault for the time period 1988-2018. They used a very similar method to Nishenko and Buland (1987), except that they modified the dimensionless coefficient of variation $\sigma=0.21$ of the lognormal distribution to account for uncertainties in the data for each fault segment.

Davies *et al.*, (1989) add two important ingredients to the lognormal model. First, they account for the time since the last earthquake in estimating σ and δ . Second, they account for the uncertainty in the parameters Γ and δ in estimating earthquake risk. Unlike Nishenko and Buland (1987), they do not assume a single worldwide value for the coefficient of variation in the lognormal process. Rather, they estimate σ and δ independently for each fault segment from earthquake history.

In this paper, we do not calculate lognormal conditional probabilities for the occurrence of the next expected strong

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earthquake ($M \geq 7$). We try to estimate or predict approximately the recurrence time τ for the occurrence of the next strong earthquake ($M \geq 7$) in the Acapulco-San Marcos fault-segment of the Mexican subduction zone.

Following Wesnousky *et al.* (1984), we consider a single fault or fault-segment. We assume that the fault or fault segment last ruptured at time R_t and further define τ for this fault as the expected time interval from R_t until the next expected rupture of the fault. Let t be the time elapsed since the most recent earthquake. Wesnousky *et al.* (1984) pointed out that they are interested in determining the probability that the next rupture time will occur during the time interval $(t, t+\Delta t)$ conditional to t years having elapsed since the last rupture at time R_t .

Following Utsu (1984), we adopt a renewal process for earthquakes. We use the following notation:

R_t : time of the last rupture of the fault or fault-segment.
 t : the time elapsed since the last rupture to present.
 τ : next expected prediction recurrence time.

Following Papoulis (1990, p. 187), the time to the next earthquake is the time interval τ from the last rupture R_t to the next rupture. This interval is a random variable $\tau \geq 0$ with distribution $F(t) = P(\tau \leq t)$. The difference

$$R(t) = 1 - F(t) = P(\tau > t) \quad (1)$$

is the earthquake system reliability. And $F(t)$ is the probability that the earthquake system rupture prior to time t , and $R(t)$ is the probability that the earthquake system function at time t . The conditional distribution

$$F(\tau | \tau > t) = \frac{P(\tau \leq \tau, \tau \geq t)}{P(\tau \geq t)} \quad (2)$$

is the probability that the earthquake system will fail prior to time τ .

Clearly, $F(\tau | \tau > t) = 0$ if $\tau < t$ and

$$F(\tau | \tau > t) = \frac{F(\tau) - F(t)}{1 - F(t)}, \quad \tau > t. \quad (3)$$

Differentiating with respect to τ , we obtain the conditional density

$$f(\tau | \tau \geq t) = \frac{f(\tau)}{1 - F(t)}, \quad \tau > t, \quad (4)$$

where $f(\tau | \tau \geq t) dT$ is the probability that the earthquake system will rupture in the time interval $(\tau, \tau + d\tau)$, assuming that it has not ruptured at time t .

THE CRITERION OF MAXIMUM CONDITIONAL PROBABILITY DENSITY

We have obtained the conditional probability density of earthquake occurrence $f(\tau | \tau \geq t)$, equation (4). This equation represents the occurrence of fractures (or earthquakes) in the earthquake system. Thus, assuming a probability distribution $f(\tau)$ for the recurrence times (τ), it is possible to obtain a theoretical conditional probability density model of earthquake occurrence based on a mathematical theory.

A reasonable prediction criterion for the occurrence interval τ between the last and the next earthquake is the one which maximizes the conditional probability density $f(\tau | \tau \geq t)$. It is the mode of the conditional probability

$$\frac{\partial}{\partial \tau} f(\tau | \tau \geq t) = 0. \quad (5)$$

So the estimator of $\hat{\tau}$ is the solution of equation (5).

Next, we discuss the application of equations (4) and (5), using the gamma and lognormal distributions models.

THE GAMMA PROBABILITY DENSITY MODEL

A distribution which plays an important role in statistics is the gamma distribution. According to Blake (1979), τ has a gamma probability distribution if its probability density function is given by

$$f(\tau) = \frac{\gamma^\alpha}{\Gamma(\alpha)} \tau^{\alpha-1} e^{-\gamma\tau}, \quad \tau > 0. \quad (6)$$

This distribution depends of two parameters α and γ of which we require $\alpha > 0, \gamma > 0$.

If τ has a gamma distribution given by equation (6) we have the mean and variance

$$E(\tau) = \frac{\alpha}{\gamma} \quad (7)$$

and

$$V(\tau) = \frac{\alpha}{\gamma^2}. \quad (8)$$

The cumulative distribution for the lognormal random variable is

$$F(\tau) = \int_0^\tau \frac{\gamma^\alpha}{\Gamma(\alpha)} s^{\alpha-1} e^{-\gamma s} ds. \quad (9)$$

It should be noted that the gamma cumulative distribution may be estimated by numerical methods.

The gamma probability density function takes on a wide variety of shapes depending on its two parameters α and γ , and is a useful probability density function in terms of modeling random phenomena.

If $\alpha=1$, then the probability density function of τ is

$$f(\tau) = \gamma \exp(-\gamma\tau), \quad \tau > 0, \gamma > 0 \quad (10)$$

which is simply an exponential random variable with parameter γ .

Substituting equation (6) and (9) in equation (4) we obtain the gamma conditional probability density of earthquake occurrence, as follows

$$f(\tau|\tau \geq t) = \frac{\frac{\gamma^\alpha}{\Gamma(\alpha)} \tau^{\alpha-1} e^{-\gamma\tau}}{1 - \int_0^t \frac{\gamma^\alpha}{\Gamma(\alpha)} s^{\alpha-1} e^{-\gamma s} ds} \quad (11)$$

It should be noted that since the observed elapsed time t is a constant, the cumulative distribution of the gamma random variable in equation (11) is a constant equal C . Thus, we can write the gamma conditional probability density of earthquake occurrence, equation (11), as follows

$$f(\tau|\tau \geq t) = W \frac{\gamma^\alpha}{\Gamma(\alpha)} \tau^{\alpha-1} e^{-\gamma\tau}, \quad (12)$$

where $W = \frac{1}{1-C}$.

Now, we proceed to find the recurrence time ($\hat{\tau}$) which maximizes the gamma conditional probability density of earthquake occurrence, equation (12). We find the maximum of $f(\tau|\tau \geq t)$ by calculating its derivative and setting it equal to zero, as follows

$$\frac{d}{d\tau} f(\tau|\tau \geq t) = \frac{\gamma^\alpha}{\Gamma(\alpha)} \tau^{\alpha-1} e^{-\gamma\tau} \left\{ \frac{(\alpha-1)}{\tau} - \gamma \right\} = 0. \quad (13)$$

From equation (13), the maximum of $f(\tau|\tau \geq t)$ appears at

$$\hat{\tau}_g = \frac{\alpha-1}{\gamma}, \quad (14)$$

except that if $\alpha < 1$, the maximum falls outside the range of definition ($x \geq 0$) and in this case the conditional probability density of earthquake occurrence is a monotonically decreasing function to 0 when $x \rightarrow \infty$.

THE LOGNORMAL PROBABILITY DENSITY MODEL

According to Sornette and Knopoff (1997), the estimate of the time until the next earthquake depends on a precise estimate of the tail of the probability density function model and is unstable with respect to presently available data for the occurrence of large earthquakes.

The lognormal model is an example of a distribution whose tail decays slower than an exponential. The lognormal distribution is similar in tail shape to the Rayleigh distribution near time $t=0$ but has a much more slowly decaying tail for large times. One important characteristic of the lognormal distribution is that the ‘‘tail’’ of the distribution is higher than for the normal distribution, so that events several standard deviations from the mean are more likely than for a normally distributed variable.

It is necessary to define mathematically the lognormal distribution. According to Cooper and McGillen (1971) the lognormal distribution is a two-parameter family of distributions, the parameters being σ_Y^2 and \bar{Y} . The lognormal probability density function is

$$f(\tau) = \frac{1}{\tau \sigma_Y \sqrt{2\pi}} e^{-(\ln \tau - \bar{Y})^2 / 2\sigma_Y^2} \quad (15)$$

If the random variable τ has a lognormal distribution with probability density function given by equation (15), the mean is

$$E(\tau) = e^{\bar{Y} + \frac{1}{2}\sigma_Y^2} \quad (16)$$

and the variance is

$$V(\tau) = e^{2\bar{Y} + \sigma_Y^2} \left(e^{\sigma_Y^2} - 1 \right). \quad (17)$$

The cumulative distribution for the lognormal random variable is

$$F(\tau) = \int_0^\tau \frac{1}{S \sigma_Y \sqrt{2\pi}} e^{-(\ln s - \bar{Y})^2 / 2\sigma_Y^2} ds. \quad (18)$$

It should be noted that the lognormal cumulative distribution must be evaluated by numerical methods.

Substituting equations (15) and (18) in equation (4), we obtain the lognormal conditional probability density of earthquake occurrence

$$f(\tau|\tau \geq t) = Q \frac{\frac{1}{\tau\sigma_y\sqrt{2\pi}} e^{-\frac{(\ln \tau - \bar{Y})^2}{2\sigma_y^2}}}{1 - \int_0^t \frac{1}{s\sigma_y\sqrt{2\pi}} e^{-\frac{(\ln s - \bar{Y})^2}{2\sigma_y^2}} ds} \quad (19)$$

It should be noted that since the observed elapsed time t is a constant, then, the cumulative distribution of the lognormal distribution $F(t)$ is equal to a constant D . Thus, we can write the lognormal conditional probability of equation (19), as follows:

$$f(\tau|\tau \geq t) = Q \frac{1}{\tau\sigma_y\sqrt{2\pi}} e^{-\frac{(\ln \tau - \bar{Y})^2}{2\sigma_y^2}}, \quad (20)$$

where

$$Q = \frac{1}{1 - D}.$$

To estimate the prediction recurrence time $\hat{\tau}_{in}$, we find the maximum of the lognormal conditional probability density $f(\tau|\tau \geq t)$, equation (20), by calculating its derivative, and setting it equal zero, as follows

$$\frac{d}{d\tau} f(\tau|\tau \geq t) = Q \frac{d}{d\tau} \left\{ \frac{1}{T\sigma_y\sqrt{2\pi}} e^{-\frac{(\ln \tau - \bar{Y})^2}{2\sigma_y^2}} \right\} = 0 \quad (21)$$

from which we obtain the mathematical condition

$$\left[(\ln \tau - \bar{Y}) + \sigma_y^2 \right] e^{-\frac{(\ln \tau - \bar{Y})^2}{2\sigma_y^2}} = 0 \quad (22)$$

from which we obtain the equation

$$(\ln \tau - \bar{Y}) + \sigma_y^2 = 0 \quad (23)$$

and the solution

$$\ln \tau = \bar{Y} - \sigma_y^2. \quad (24)$$

Using equation (24) we can estimate or predict the lognormal recurrence of the next expected large earthquake event.

It should be noted that in the theory of the conditional probability density by definition of recurrence time the predicted recurrence time includes the elapsed time t . However, equation (24) indicates that for the lognormal model predicted recurrence time $\hat{\tau}_{in}$ is independent of the elapsed time t since the last large earthquake.

In order to apply the lognormal probability density model, it is first necessary to estimate the parameter σ_y^2 and the parameter \bar{Y} of the lognormal distribution.

Assuming that the distribution of recurrence times in the Acapulco-San Marcos fault-segment can be represented by the lognormal probability distribution and the estimated sample mean and sample variance are represented by μ and ν , respectively, the equations (16) and (17) may be used to determine the lognormal parameters σ_y^2 and \bar{Y} directly (see Winkler and Hays, 1975, p. 516) as follows:

$$\mu = e^{\bar{Y} + \frac{1}{2}\sigma_y^2} \quad (25)$$

and

$$\nu = e^{2\bar{Y} + \sigma_y^2} (e^{\sigma_y^2} - 1). \quad (26)$$

To solve these two equations simultaneously, we note that

$$\mu^2 = \left\{ e^{\bar{Y} + \frac{1}{2}\sigma_y^2} \right\}^2 = e^{2\bar{Y} + \sigma_y^2}. \quad (27)$$

Substituting equation (27) in equation (26) and solving for σ_y^2 , we obtain

$$\sigma_y^2 = \ln \left\{ \frac{\nu}{\mu^2} + 1 \right\} \quad (28)$$

and from equation (27), we obtain

$$\bar{Y} = \ln \mu - \frac{1}{2}\sigma_y^2. \quad (29)$$

Substituting equation (28) in equation (29), we obtain

$$\bar{Y} = \ln \mu - \frac{1}{2} \left\{ \ln \left(\frac{\nu}{\mu^2} + 1 \right) \right\}. \quad (30)$$

THE ACAPULCO-SAN MARCOS SEGMENT

Selection criteria for choosing sequences for earthquake catalogs have not been formalized. Thus selection of boundaries for a fault-segment is not a rigorous process for which one set of rules can apply to all situations. At present rupture dimensions of past large earthquakes are commonly used to define dimensions of current seismic segments.

The boundaries of the Acapulco-San Marcos fault-segment were defined on the basis of great and large

earthquakes and their associated aftershocks by McNally, (1981); Singh *et al.*, (1982); Nishenko and Singh, (1987, a, b). McNally (1981) suggests that the boundaries for the Acapulco area may be based on the aftershock zone of the 1957 ($M_s=7.5$) earthquake. The last major earthquakes ($M_s>7.5$) in this general region occurred in 1957 ($M_s=7.5$), 1937 ($M_s=7.5$) and 1907 ($M_s=8.0$). Singh *et al.* (1982) pointed out that the earthquake of 1845, which generated tsunami waves at Acapulco most probably ruptured the same area as the 1907 and 1957 events. The 1820 event, which also generated a tsunami at Acapulco, quite likely ruptured the same area.

Thus the most likely seismic area for the Acapulco-San Marcos fault-segment is between latitudes $16.6^\circ-17.7^\circ$ N and longitudes $98.1^\circ-99.6^\circ$ W. The events that occurred in this region between 1820 and 1989 are listed in Table 1.

Table 1

Catalog of strong earthquakes ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment of the Mexican subduction zone, during the period 1820-1989. Source Anderson *et al.* (1994).

Occurrence date	Occurrence date (yrs.)	Lat. ($^\circ$ N)	Long. ($^\circ$ W)	Recurrence time (yrs.)	Magnitude M_s
1820-05-04	1820.43	17.2	99.6		7.6
1845-04-07	1845.35	16.6	99.2	24.92	8.1
1874-03-16	1874.29	12.7	99.1	28.94	7.3
1907-04-15	1907.37	16.7	99.2	33.08	7.7
1937-12-23	1938.06	17.1	98.1	30.69	7.5
1957-07-28	1957.66	17.1	99.1	19.60	7.5
1989-04-25	1989.40	16.6	99.5	31.74	6.9

Following Olsson (1982) and Utsu (1984), in the case where more than one large earthquake has taken place within a short time interval, we may consider all but the largest as aftershocks and eliminate them from Table 1.

ESTIMATE OF THE GAMMA PREDICTION

Using the data given in Table 1 for the Acapulco-San Marcos fault-segment, we estimate the sample mean $\mu=28.1617$ and sample variance $v=25.56066$. Next we estimate the parameter α and γ . To do this, equations (7) and (8) and the estimated sample mean $\mu=28.1617$ and sample variance $\gamma=25.56066$ (see Winkler and Hays, 1975, p. 516), as follows

$$\mu = \frac{\alpha}{\gamma} \quad \text{and} \quad v = \frac{\alpha}{\gamma^2} . \quad (31)$$

We calculate α and γ , solving equations (31) simultaneously, and we find $\alpha=31.02742$ and $\gamma=1.10176$.

To estimate or predict the recurrence time ($\hat{\tau}_g$), using the gamma model, we substitute the values of the parameters in equation (14) and we obtain

$$\hat{\tau}_g = \frac{31.02742 - 1}{1.10176} = 27.25 \text{ (yrs) .}$$

Finally, we estimate or predict the occurrence time of the next expected strong earthquake ($M_s \geq 7$). To do this we add to the predicted gamma recurrence time $\hat{\tau}_g=27.25$ (yrs.) the occurrence time of the last observed earthquake $R_i=1989.40$. Thus we conclude that using the gamma model, the next large earthquake may occur approximately before the year 2016.65, or equivalently before August 2016.

PREDICTION ERROR FOR THE GAMMA PREDICTION

Following Benjamin and Cornell (1976, p. 176), any predictor of τ , say $\hat{\tau}$, has a square error:

$$\epsilon^2 = E[(\tau - \hat{\tau})^2] = Var[\tau] + (\mu_\tau - \hat{\tau})^2, \quad (32)$$

where μ_τ is the mean of the sample $\{\tau_i\}$.

Using the data given in Table 1, we have calculated $\mu_\tau=28.1617$ (yrs.) and $Var[\tau]=25.56066$ (yrs²). Thus using equation (32) we estimate the square error (ϵ^2) for the predicted gamma recurrence time $\hat{\tau}_g=27.25$ (yrs.) as follows:

$$\epsilon_g^2 = 25.56066(yrs^2) + (28.1617yrs - 27.25yrs)^2 = 29.39186(yrs^2)$$

or equivalently

$$\epsilon_g = \pm 5.14 \text{ (yrs.)}$$

Using this value of the prediction error, the gamma occurrence time of the next expected strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment can be written $t_g=August 2016 \pm 5.14$ yrs.

ESTIMATE OF THE LOGNORMAL PREDICTION

Using the data given in Table 1 we have estimated the sample mean $\mu=28.1617$ and sample variance $\gamma=25.56066$. To estimate the parameters σ_Y^2 and \bar{Y} we use equations (28) and (30), and we obtain $\sigma_Y^2=0.02956$ and $\bar{Y}=3.32454$.

To estimate or predict the recurrence time ($\hat{\tau}_m$) using the lognormal model, we substitute the values of the parameters $\bar{Y}=3.32454$ and $\sigma_Y^2=0.02956$ in equation (24) and we obtain

$$\ln \hat{\tau} = \bar{Y} - \sigma_y^2 = 3.32454 - 0.02956$$

from which we obtain

$$\hat{\tau}_{\ln} = 27.20 \text{ (yrs) .}$$

Next, to estimate or predict the lognormal occurrence time of the next strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment, we add to the predicted recurrence time $\hat{\tau}_{\ln} = 27.20$ (yrs) the occurrence time of the last observed earthquake $R_t = 1989.40$. Thus, we conclude that the next expected strong earthquake in the Acapulco-San Marcos may occur approximately before the year 2016.60 or equivalently before July 2016.

PREDICTION ERROR FOR THE LOGNORMAL PREDICTION

Using the data given in Table 1, we have calculated $\mu_{\tau} = 28.1617$ (yrs) and $\text{Var} [\tau] = 25.56066$ (yrs²). Using equation (32) we estimate the square error (ϵ^2) for the predicted lognormal recurrence time ($\hat{\tau}_{\ln} = 27.20$ yrs) as follows:

$$\epsilon_{\ln}^2 = 25.56066(\text{yrs}^2) + (28.1617 \text{ yrs} - 27.20 \text{ yrs})^2 = 26.48553(\text{yrs}^2)$$

or equivalently

$$\epsilon_{\ln} = \pm 5.15 \text{ (yrs) .}$$

Using this value of the error, the lognormal occurrence time of the expected strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment can be written

$$t = \text{July } 2016 \pm 5.15 \text{ (yrs) .}$$

CONCLUSIONS

We attempted a probabilistic analysis of the problem of forecasting the occurrence time of the next strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment of the Mexican subduction zone. In order to do this, we use the conditional probability density of earthquake occurrence and the criterion that the conditional probability density of earthquake occurrence is a maximum when the earthquake occur.

We have adopted the gamma distribution and the lognormal distribution models because Nirigasawa (1972), Rikitake (1976), Utsu (1984) and Jacob (1984) carried out statistical studies of the recurrence time interval for great earthquakes mostly occurring at a number of subduction zones. They generally concluded that the gamma or lognormal distribution fit most of the existing recurrence data fairly well.

In addition, we have adopted the lognormal distribution to determine the conditional probability density of earthquake occurrence, to illustrate improvements in probabilistic earthquake prediction methodology and facilitate the comparison with previous applications of the lognormal distribution to earthquake prediction studies.

The lognormal distribution has been used for earthquake conditional probabilistic studies for about 20 years. The new contribution here is to use it to make the prediction of the future recurrence time t of the next expected large earthquake. To do this we introduce the conditional probability density and the criterion that the conditional probability density is maximum when the new earthquake occurs.

We estimate a recurrence time $\hat{\tau}_g = 27.25$ (yrs) with an error $\epsilon_g = \pm 5.14$ (yrs) for the occurrence of the next expected strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment, using as criterion the maximum of the gamma conditional density $f(\tau | \tau \geq t)$ of earthquake occurrence. We also estimate or predict a recurrence time $\hat{\tau}_{\ln} = 27.20$ (yrs) with a prediction error $\epsilon_{\ln} = \pm 5.15$ (yrs.) for the occurrence of the same expected strong earthquake ($M_s \geq 7$) in the Acapulco-San Marcos fault-segment, assuming as criterion of the maximum of the lognormal conditional density $f(\tau | \tau \geq t)$ of the earthquake occurrence.

Thus we conclude that both predictions agree that a strong earthquake ($M_s \geq 7$) may occur in the year 2016 in the Acapulco-San Marcos fault-segment. This highly damaging earthquake will affect the city of Mexico.

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