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U.S. GEOLOGICAL SURVEY
Reston, VA 22092

Memorandum

Date 12/5/78

To: Branch of Plans and Program Management, Publications Division -

From: Chief, Office of Scientific Publications

Subject: New USGS open-file report

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TITLE: A technique for the rapid estimation of earthquake losses

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CONTENTS: 100 p., ____ pls., 59 figs.

Map scale: ____

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Papercopy price:	Microfiche price:	Release date: DEC. 1978
		Area: --
		Report No. 78-440

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Development of A Technique for the Rapid Estimation of Earthquake Losses

by

S. T. Algermissen, M. B. McGrath, and S. L. Hanson

Open-File Report 78-440

1978

Prepared for the Office of Policy Development and Research and the Federal Insurance Administration, Department of Housing and Urban Development under Interagency Agreement IAA-H-32-71

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SUMMARY

A simple, general technique has been outlined for the rapid, approximate estimation of building losses resulting from ground shaking during earthquakes. The technique has been applied to the San Francisco Bay area. Ground shaking, ground failures of various kinds, surface faulting, tsunamis, and earthquake induced fires are all responsible for earthquake building losses. Only losses associated with ground shaking are considered in this report for a number of reasons. Losses associated with various types of ground failure such as landsliding and liquefaction are difficult to estimate because the conditions necessary for these effects to occur are not completely understood and/or may be difficult to identify. Losses related to surface faulting are believed to be small as a proportion of total losses (Algermissen and others, 1972), and losses related to tsunamis have been quite rare along the central California coast. Well-established methods are available for estimating fire losses, but these losses are beyond the scope of this report.

The technique outlined here for the estimation of ground shaking damage depends upon a building classification, building inventory, loss-ground shaking (intensity), and intensity-attenuation relationships developed in previous studies. The general method can be used anywhere, but it is dependent on inventory development, regional construction practice, and adjustment of loss-intensity and intensity-attenuation

relationships to fit the area considered. The method outlined in this report, if exploited fully, should be a valuable tool for Federal, State, and local agencies involved with disaster preparedness and post-earthquake relief and rehabilitation.

Even a very quick field inspection of the most heavily damaged area following an earthquake will greatly improve damage estimates if (1) the center of heaviest damage is located and any surface faulting or other geologic effect identified from the field inspection and (2) the data obtained from the field inspection are used in conjunction with the estimation method outlined in this report.

For some classes of buildings, losses are about the same for an earthquake with I_o=IX on the Hayward fault as for an earthquake with I_o=X on the San Andreas fault. The largest percent loss for any large earthquake in the San Francisco Bay area is about 29 percent of replacement value for certain concrete frame buildings (subclass 4HD) greater than four stories in height.

ACKNOWLEDGMENTS

The development of inventory technique and loss-intensity relationship by K. V. Steinbrugge in previous papers has made the present report possible. Reva Tibbetts patiently typed several drafts and the final manuscript.

INTRODUCTION

Techniques for the estimation of earthquake losses have been developed in a series of reports prepared for the Department of Housing and Urban Development since 1967. Recently, methods for estimation of losses to dwellings (Rinehart and others, 1976) and to buildings other than dwellings (Algermissen and others, 1977) have been improved and modified. The reports cited above make use of the San Francisco Bay area as a pilot study. The general techniques applied are, however, believed to be applicable to many other metropolitan areas with an earthquake hazard.

It would be extremely useful if order-of-magnitude earthquake losses could be estimated within a short time following an earthquake. Reports within a few hours or days following a damaging earthquake are usually based on press reports, which are often greatly distorted and not rationally based. The initial post-earthquake planning of many Federal agencies involved in disaster relief and reconstruction, as well as many businesses in the private sector, would greatly benefit from a rapidly available (1-6 hours after the event), even though crude, estimate of the losses.

OBJECTIVE

The objective of this report is to outline a technique for the rapid estimation of earthquake losses associated with ground shaking and to demonstrate the technique in the San Francisco Bay area[1] (fig. 1). The applicability of the technique to other areas of the country will also be discussed.

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[1]The San Francisco Bay area is considered to be made up of: San Francisco, San Mateo, Santa Clara, Alameda, Contra Costa, Solano, Napa, Sonoma, and Marin Counties, Calif.

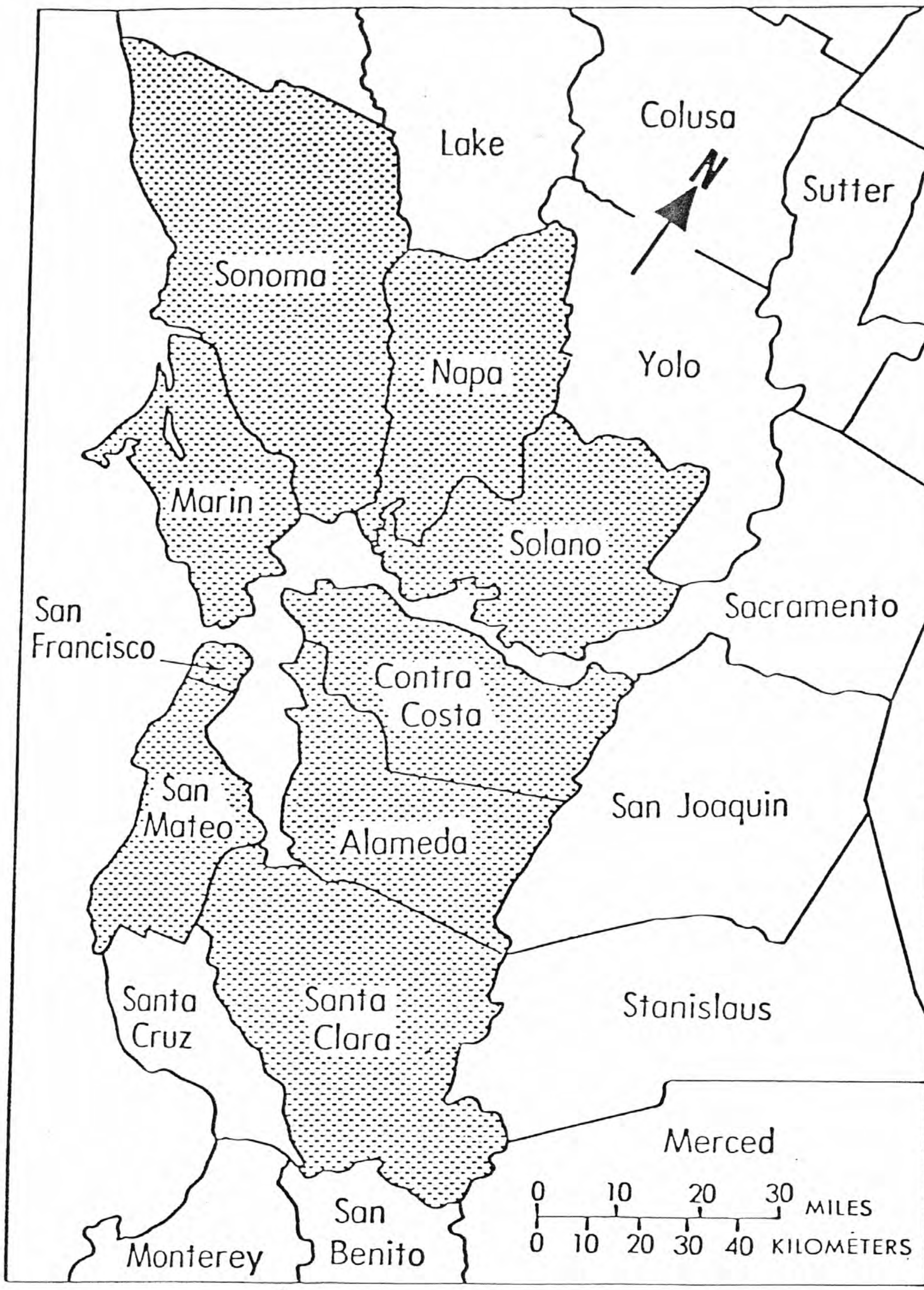

Figure 1.--Location map of northern California showing the nine-county area studied in this report.

BUILDING CLASSIFICATION

The building classification considered appropriate for use in this report is that developed by Steinbrugge. (See Algermissen and others, 1977.) An abridged version of the building classification is given in table 1, together with a notation that is compatible with and used to identify computer loss output in later tables. A more complete description of the classification is given in table A1 in the appendix.

Table 1.--Notation used to identify building classes in computer outputs

Notation used in loss tables	Brief description of building subclass (see table Al for complete description
2A	One story all metal; floor area less than 20,000 ft^2
2B	All metal buildings not under 2A
3LA	Steel frame, superior damage control features; less than 4 stories
3LB	Steel frame; ordinary damage control features; less than 4 stories
3LC	Steel frame; intermediate damage control features (between 3LA and 3LB); less than 4 stories
3LD	Floors and roofs not concrete; less than 4 stories
3HA 3HB 3HC 3HD	Descriptions of 3HA, 3HB, 3HC, and 3HD are the same as 3LA, 3LB, 3LC, and 3LD except that they designate buildings with 4 stories and over
4LA	Reinforced concrete; superior damage control features; less than 4 stories
4LB	Reinforced concrete; ordinary damage control features, less than 4 stories
4LC	Reinforced concrete; intermediate damage control features (between 4LA and 4LB), less than 4 stories
4LD	Precast reinforced concrete, lift slab, less than 4 stories
4LE	Floors and roofs not concrete, less than 4 stories

Table 1.--Notation used to identify building classes in computer outputs--Continued

Notation used in loss tables	Brief description of building subclass (see table A1 for complete description)
4HA 4HB 4HC 4HD 4HE	Descriptions of 4HA, 4HB, 4HC, 4HD, and 4HE are the same as 4LA, 4LB, 4LC, 4LD, and 4LE except that they designate buildings with 4 stories and over
5B	Mixed construction, see table A1
5C	Do.
5D	Do.
5E	Do.

DEVELOPMENT OF THE TECHNIQUE

Introduction

The estimation of building damage depends upon: (1) the geographical distribution of buildings by class of construction (the inventory) in the area considered, (2) the nature of the ground shaking, and (3) the relationships between (1) and (2) that result in building damage.

In previous studies, methods were developed to obtain the inventory, approximate the ground shaking, and relate degree of ground shaking to percent loss in buildings (Steinbrugge and others, 1969; Algermissen and others, 1969; Rinehart and others, 1976; Algermissen and others, 1977).

The major effort in this report is to develop a quick, approximate method of loss estimation making use of inventory, loss, and ground shaking relationships previously reported.

The method proposed for rapid estimation of building losses associated with ground shaking is quite straightforward. In outline the steps are:

1. Develop an inventory of buildings of interest (buildings or other facilities for which it is of interest to develop loss estimates.)
2. Develop building loss-intensity of ground shaking relationships for the building classes of interest over the range of ground shaking likely to be experienced in the area of interest.
3. Develop ground motion attenuation relationships.

4. Compute losses for all earthquakes likely to occur in the area of interest using the relationships listed in (1) through (3) above.

In this study, earthquakes with maximum Modified Mercalli intensities of VI through X were assumed possible in the San Francisco Bay area (SFBA). Earthquakes with maximum intensities of IX and X were assumed to occur only on the San Andreas and Hayward faults; earthquakes with maximum intensities of VI through VIII were assumed to be likely anywhere in the San Francisco Bay area. Consequently losses for earthquakes with maximum intensities of VI through VIII were computed for a grid of points throughout the SFBA. The contoured results make possible the rough estimation of earthquake losses regardless of the location of the shock in the area.

Causes of Building Damage

Building damage in earthquakes is related to three principal causes: (1) ground shaking, (2) ground failure, and (3) tsunami or wave damage, as well as to (4) secondary effects such as fire. Only damage related to ground shaking is considered in this report. (Ground shaking is considered to be the major cause of building damage and loss.) Ground failure is taken here to mean any of a number of different kinds of ground disturbances such as surface faulting, landsliding of various kinds, liquefaction, and so forth. Surface faulting is common in California and Nevada earthquakes and is relatively predictable; for the remainder of the country, it is virtually unknown. The relationships between landsliding and ground shaking are as yet poorly understood, and detailed landslide mapping has been done in relatively few areas of the country. The relationships between liquefaction and ground shaking are somewhat better understood at the present time than the landsliding-ground shaking relationships. As with landslides, comparatively few areas of the country have been investigated for liquefaction potential. Even where considerable effort has been expended in mapping areas of liquefaction potential such as the San Francisco Bay area (Borcherdt, 1975), it is not possible to specify what percentage of areas identified as having high liquefaction potential will actually liquefy during an earthquake. It is, however, fairly certain that in the case of the San Francisco Bay area, only a small percentage of the areas mapped as having liquefaction (or landslide) potential will actually fail in any particular earthquake.

Building Inventory

Two methods have been developed in previous studies for obtaining building inventory, one for single-family wood frame dwellings (Steinbrugge and others, 1969; Algermissen and others, 1969; Rinehart and others, 1976) and a second method for other types of buildings (Algermissen and others, 1977).

The inventory for single-family dwellings in California has been obtained from United States census data. Certain characteristics of single-family dwellings, together with the number of single-family dwellings in each census tract and their value, are all available on magnetic tape. The census information by itself does not provide sufficient information to classify dwellings for earthquake damage evaluation. In previous studies in California, census data were supplemented by statistical sampling of dwelling construction characteristics (Steinbrugge and others, 1969). Brick dwellings were not evaluated in California, because they constitute less than 5 percent of the dwellings in the state. The percentage of brick dwellings in the Eastern United States far exceeds 5 percent. Consequently, application of the loss estimation technique to dwellings in the Eastern United States would require an inventory of brick dwellings, since their loss characteristics are quite different than for wood frame structures. The ratio of brick to wood frame dwellings can, in general, be obtained throughout the country using the census data augmented by statistical sampling.

The technique for obtaining inventory for buildings other than wood frame dwellings was developed by Steinbrugge (Algermissen and others, 1977) in the San Francisco Bay area. In general, the inventory is obtained by: (1) assuming that a direct correlation exists between specific building classes and land-use designations; (2) assuming that all buildings (of a particular class) are uniformly distributed within particular land-use zones. The importance of this assumption is that it leads to the generalization that building values (of a particular class) are, on the average, the same per unit area throughout any area considered. This equal distribution of building value is reasonably consistent with the policy normally used in zoning ordinances formulated by planning commissions and regional agencies; (3) assuming that nonconforming uses are not included in the above distribution of building classes. The inventory developed for the San Francisco Bay area was field checked for validity and consistency throughout the area.

The use of this inventory technique outside of the San Francisco Bay area would require the land-use classifications in the region in question to be reasonably consistent with practice in the Bay area. Even verification of consistent land-use classification requires considerable study. If land-use classifications are different from those in the Bay area, the inventory technique used here could probably be adapted. For areas where land-use classifications are radically different or nonexistent, considerable research would be necessary to develop an inventory, and it might not be economically feasible to develop a usable inventory.

Estimation of Ground Motion

Modified Mercalli intensity (MMI) is the parameter used to describe ground motion in this report. Earthquakes with maximum MMI's (I_o's) greater than eight in the San Francisco Bay area were assumed to occur only along two major faults: the San Andreas and Hayward faults. Specific isoseismal maps were prepared for earthquakes with epicenters along the two faults. Figure 2 is an example (Algermissen and others, 1977). For earthquakes $VI \leq I_o \leq VIII$, average isoseismal maps were used. Length and direction of faulting were taken into account, isoseismals being elongated in the direction of faulting. Site amplification corrections to the average isoseismals were made based on the surficial geology in each census tract. The method used to construct the isoseismal maps, including the site corrections, is completely described in another report (Algermissen and others, 1977).

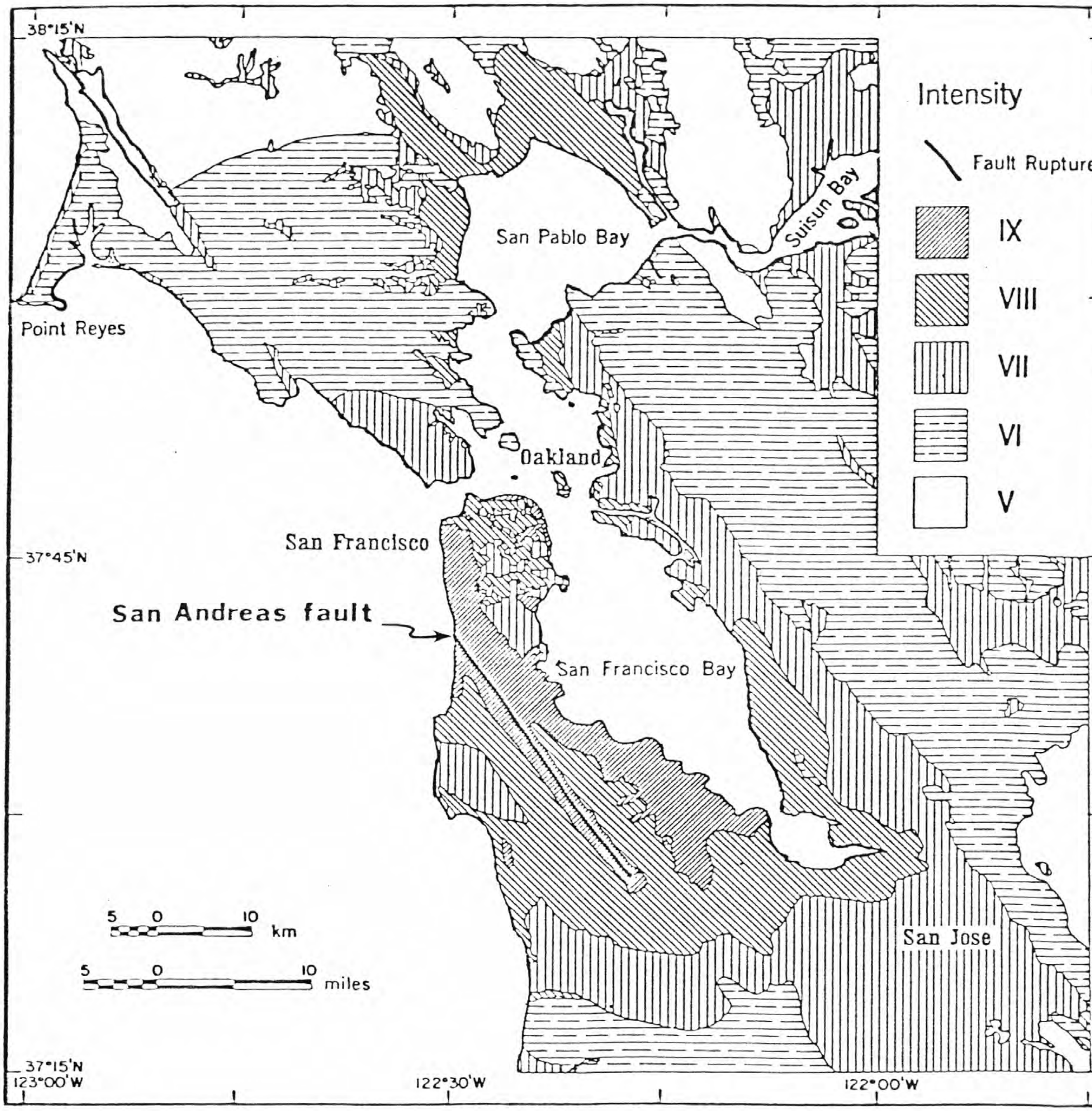

Figure 2.--Isoseismal map for a maximum intensity-IX earthquake on the San Andreas fault.

The Rapid Estimation of Losses

Introduction and assumptions.--The area selected for a pilot study is the San Francisco Bay area (SFBA) consisting of San Francisco, San Mateo, Santa Clara, Alameda, Contra Costa, Solano, Napa, Sonoma, and Marin Counties. Inventories of buildings exposed to risk as of 1970 were already available (Algermissen and others, 1977).

Some assumptions were made regarding the possible locations of earthquakes in the SFBA.

1. It was assumed that the largest earthquake that could reasonably occur in the SFBA would have an I_o of X.
2. Earthquakes with I_o's of X were constrained to occur on the San Andreas fault. Earthquakes with I_o=IX were considered to be the largest probable earthquake on the Hayward fault. Earthquakes with I_o=IX were also considered possible on the San Andreas fault. Because of the probable length of faulting (200-400 km) involved with large earthquakes on either of these two faults, the epicenter of possible earthquakes is relatively unimportant. Ground motion is assumed to attenuate approximately perpendicular to the direction of faulting in the earthquake and not radially from the instrumentally determined epicenter of the earthquake. The losses in the SFBA will be about the same regardless of the position of the epicenter on the fault.
3. The occurrence of earthquakes with I_o's of VI through VIII was considered to be possible anywhere in the SFBA.

4. Earthquakes with maximum MMI's of less than VI were not considered since the resulting losses would be small.

5. For the purpose of demonstrating the loss estimation technique, losses were calculated in terms of the percent loss by class of construction. Percent loss is defined to mean the average percentage of the total actual cash value required to fully repair in kind any building of a particular class experiencing ground motion represented by a particular degree of the MMI scale.

For earthquakes with maximum MMI's from VI to X in the SFBA, approximate percent losses may be quickly obtained as follows:

Earthquakes with maximum MMI's (I_o's) of IX or X.--These earthquakes are assumed to occur only on the San Andreas (I_o=IX and X) or Hayward (I_o=IX) faults in the pilot area. Because of the great length of faulting associated with large earthquakes (I_o=IX or X) in the SFBA, the intensity distribution for an earthquake with I_o=X, say, on the San Andreas fault is approximately the same, regardless of where the epicenter of the earthquake actually occurs on the fault, provided, of course, that the epicenter is on the San Andreas or Hayward fault in the San Francisco Bay area. Similar statements can be made for an earthquake with I_o=IX on the San Andreas fault and earthquakes with I_o=IX on the Hayward fault. Thus, as soon as the I_o of an earthquake on the San Andreas or Hayward fault is approximately determined to be IX or X after the occurrence of the earthquake, the percent losses by class of construction associated with such an earthquake can also be approximately determined. Isoseismal maps for the three earthquakes just discussed (I_o=IX and X, San Andreas fault; I_o=IX, Hayward fault) were prepared for an earlier report (Algermissen and others, 1977). An example is shown in figure 2. The approximate percent losses for various classes of construction associated with earthquakes with maximum MMI's of IX and X are given in table 2.

Table 2.--Percent loss for the San Francisco Bay area for each subclass due to a single earthquake on the San Andreas or the Hayward fault

	San Andreas		Hayward
Intensity---	IX	X	IX
2A	2.5	4.1	3.4
2B	3.2	6.1	5.8
3HA	8.1	9.3	9.4
3HB	15.3	16.7	16.8
3HC	10.2	11.7	11.8
3HD	15.3	16.7	16.8
4HA	10.2	11.7	11.8
4HB	21.9	23.9	24.0
4HC	15.3	16.7	16.8
4HD	26.3	28.7	28.8
4HE	24.1	26.3	26.4
5B	4.0	8.2	6.4
5C	8.9	13.1	11.5
5D	11.5	16.8	14.7
5E	16.8	25.2	22.4
3LA	3.2	6.6	5.2
3LB	8.9	13.1	11.5
3LC	4.0	8.2	6.4
3LD	8.9	13.1	11.5
4LA	4.0	8.2	6.5
4LB	12.7	18.7	16.4
4LC	8.9	13.1	11.5
4LD	15.3	22.4	19.7
4LE	14.0	20.5	18.0

DISCUSSION

Community estimates of direct property damage from an earthquake, at replacement cost, either from a hypothetical event or from an experienced event, consist of estimates of losses due to ground shaking, ground failure, tsunami, and earthquake induced fire.

This can be expressed as follows:

$$D_c = D_s D_g + D_t D_f$$

where

D_c = Community damage;

D_s = Community damage from ground shaking;

D_g = Community damage from ground failure (faulting, slides, liquefaction);

and D_t = Community damage from tsunami (earthquake induced surges or waves);

D_f - Community damage from earthquake induced fire.

This report considers losses resulting only from ground shaking. Ground shaking is a function of the earthquake depth, epicenter location, and geology, and for distances from the epicenter, the attenuation of the ground motion. At any site, the nature of the surficial geology will influence the degree of shaking that structures at that location will experience.

Methodologies for estimating damages from ground failure (rupture or surface faulting, landslides or liquefaction) have not yet been well developed. Similarly, methodologies for estimating damages from tsunamis have yet to be developed. Estimating damage from these phenomena will require special investigation.

Fire departments and insurance adjusters have well established methods for estimating fire loss. For that reason the question of estimating such loss after an earthquake is not pursued in this discussion.

The methodologies discussed herein, therefore, will be confined to D_s, community damage from ground shaking.

In the absence of estimating methodologies, those who must make estimates of earthquake damage can, if they have information on structure inventory and value, make estimates of damage from ground failure or tsunami by inspection or before the fact, by making some allowance for such damage.

Community estimates of earthquake loss, at replacement cost, from ground shaking from a hypothetical earthquake would consist of estimates of damage to wood frame residences, damage to brick (or brick veneer) residences, damage to high-rise and nonresidential structures, damage to infrastructure (i.e., roads; bridges; power stations; transformers; lifelines, such as water, gas, sewers and other conduits; refineries and similar process structures), and finally, contents.

Community loss from ground shaking can be expressed by the formula:

$$D_s = D_{ws} + D_{bs} + D_{hs} + D_{is} + D_{cs}$$

where

D_s = Community damage from ground shaking;

D_{ws} = Damage from shaking to wood frame dwellings.

D_{bs} = Damage from shaking to brick or brick veneer buildings;

D_{hs} = Damage from ground shaking to buildings other than 1-4 family residences (high rise and other nonresidentialstructures); structures);

D_{is} = Damage from shaking to nonbuilding infrastructures (roads, bridges, transport, power stations, refineries, etc.);

D_{cs} = Damage to building contents from shaking.

D_{ws}, damage from shaking to wood frame dwellings can be estimated on the basis of the methodology already developed (Rinehart and others, 1976). Although based on California experience, the methodology is adaptable to other areas of the country, given the appropriate input data. Lacking such input data but with usable inventory, an estimator in other areas with a reasonable estimate of intensity could use the damage tables in this report to develop very rough estimates of damage.

Examination of tables 1 and 2, figure 3, and figures A1-A57 in the appendix reveals some interesting aspects of the nature of losses in the SFBA. Note that for certain building classes, losses are about the same for an earthquake with I_o=IX on the Hayward fault as for an earthquake with I_o=X on the San Andreas fault. For earthquakes in the SFBA with I_o's ranging from VI through VIII, those with epicenters in San Francisco Bay or near the south end of the Bay would generate the largest losses. The same generalization would undoubtedly be true for earthquakes with I_o=IX or X if these earthquakes had not been restricted to epicenters along the San Andreas and Hayward faults. The explanation for this distribution of losses is simple. Earthquakes that might occur at locations that are more or less equidistant from the industrial, commercial, and population centers of San Francisco and Oakland should produce large losses. The extension of the high-loss pattern toward the southern part of the Bay occurs because of the location of San Jose, an important population center near the south edge of the Bay.

Earthquakes with I_o's from VI to VIII.--The ground motion associated with earthquakes with moderate I_o's (VI through VIII) was estimated using average isoseismal maps plus corrections for site amplification determined for each census tract (Algermissen and others, 1977).

Since earthquakes with I_o's between VI and VIII are assumed to occur anywhere in the SFBA, a scheme had to be worked out to estimate the losses approximately, regardless of the location of the earthquake. Losses associated with earthquakes with I_o from VI to VIII were computed assuming earthquake epicenters on a grid of points in the SFBA. The grid points are 10 km apart. An example of the calculation grid and contoured percent losses is shown in figure 3. Other maps may be found in the appendix.

Percent losses for any building class of interest may then be estimated in the following manner:

1. Estimate the epicenter and maximum intensity (I_o) of the earthquake of interest.
2. For the building subclass of interest, select the appropriate map and locate the epicenter.
3. Interpolate the percent loss from the contours for the building class of interest. An example for building subclass 3LB for an intensity I_o=VII is shown in figure 3.

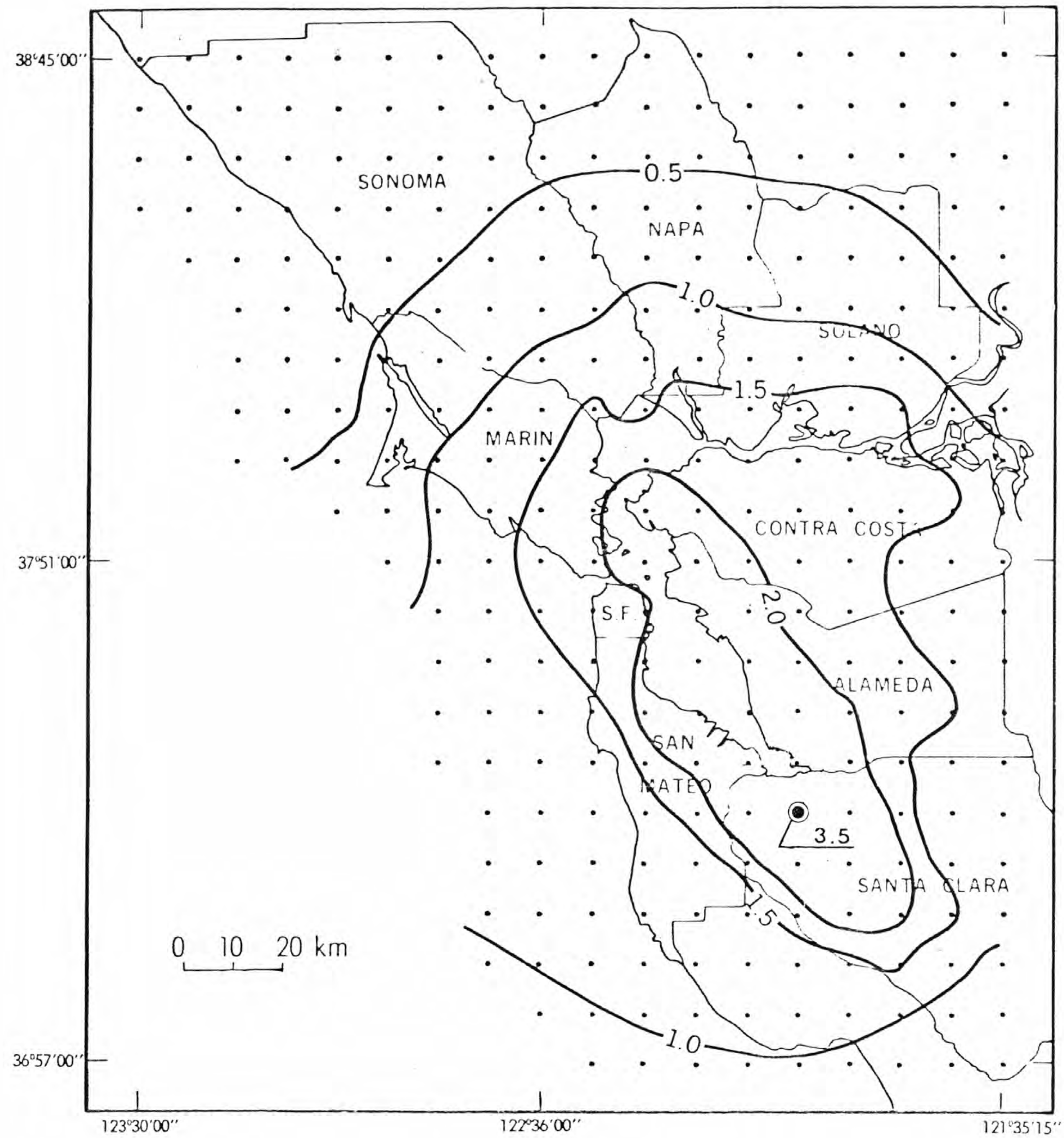

Figure 3.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LB for an earthquake with maximum intensity I_o=VII.

The contour values used for figure 3 and for the illustrations in the appendix range from 0.5-12.0 percent. If the losses for a particular building subclass are less than 0.5 percent, no contour map was prepared. Table 3 gives the maximum percent losses for each building subclass in the SFBA for earthquakes I_o=VI-VIII. Subclasses for which the maximum loss is less than 0.5 percent in table 3 (for earthquakes with I_o from VI to VIII) are marked by asterisks. No contour maps were prepared for these subclasses.

Although the losses for single-family dwellings are not demonstrated here, the basic technique and mapping would be the same.

Table 3.--Maximum percent losses by building subclass for earthquakes with maximum Modified Mercalli intensities (I_o's) of VI, VII, and VIII anywhere in the San Francisco Bay area

Intensity VI		Intensity VII		Intensity VIII	
2A	.3*	2A	1.0	2A	1.8
2B	.2*	2B	1.1	2B	2.7
3HA	.1*	3HA	.3*	3HA	.9
3HB	.4*	3HB	1.5	3HB	6.1
3HC	.1*	3HC	.4*	3HC	1.0
3HD	.4*	3HD	1.5	3HD	6.1
4HA	.1*	4HA	.4*	4HA	1.1
4HB	.6	4HB	2.2	4HB	8.8
4HC	.4*	4HC	1.5	4HC	6.1
4HD	.8	4HD	2.6	4HD	10.5
4HE	.7	4HE	2.4	4HE	9.6
5B	.1*	5B	1.0	5B	2.7
5C	1.7	5C	3.5	5C	6.4
5D	2.2	5D	4.5	5D	8.2
5E	3.6	5E	7.6	5E	13.0
3LA	.1*	3LA	.8	3LA	2.2
3LB	1.7	3LB	3.5	3LB	6.4
3LC	.1*	3LC	1.0	3LC	2.7
3LD	1.7	3LD	3.5	3LD	6.4
4LA	.1*	4LA	1.0	4LA	2.7
4LB	2.5	4LB	5.0	4LB	9.2
4LC	1.7	4LC	3.5	4LC	6.4
4LD	3.0	4LD	6.0	4LD	11.0
4LE	2.7	4LE	5.5	4LE	10.1

*Maps not prepared. Losses less than 0.5 percent.

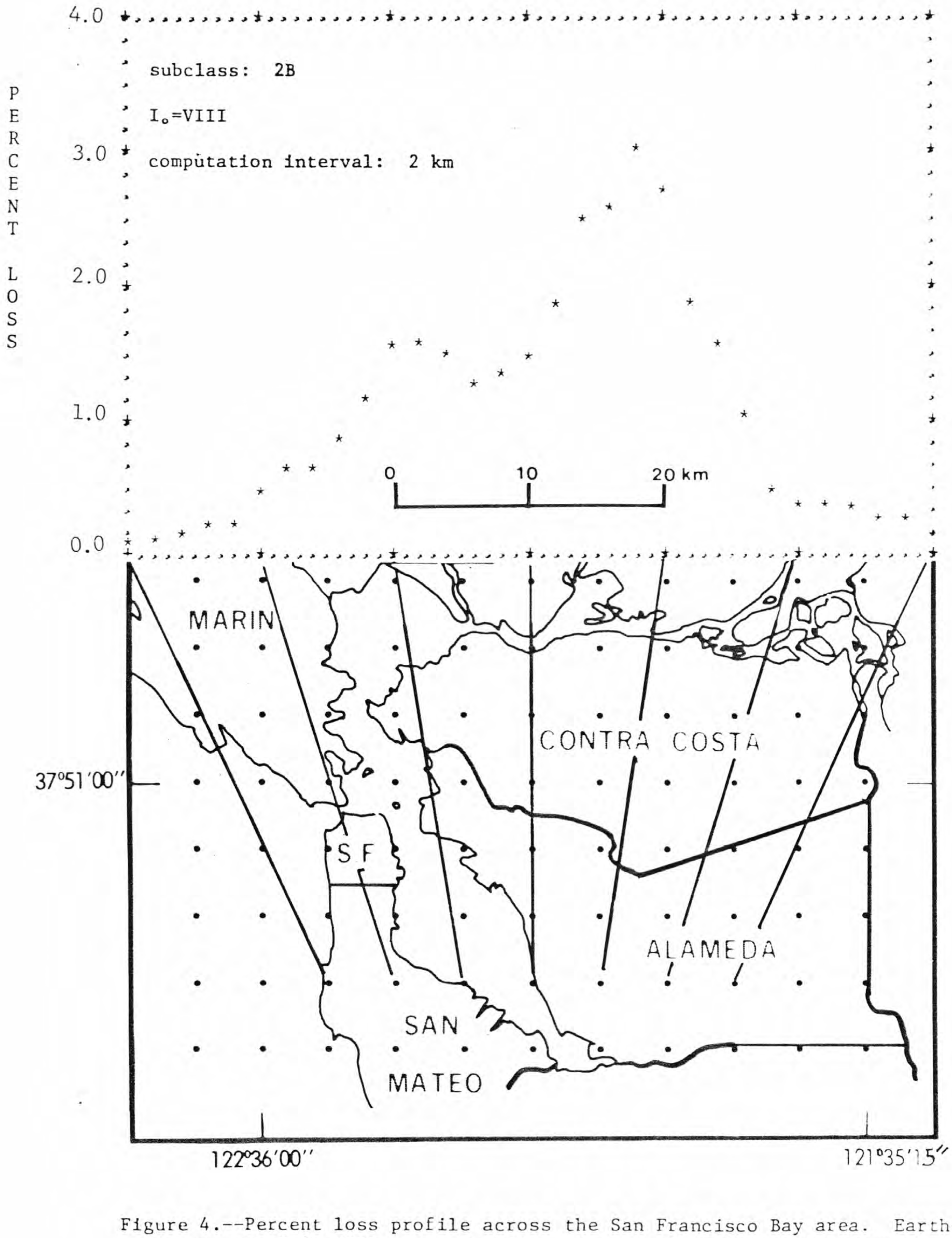

Figure 4.--Percent loss profile across the San Francisco Bay area. Earthquakes with I_o's=VIII are assumed to occur at 2-km intervals along the profile.

The 10-km grid spacing for epicenter locations and loss computations was selected because the accuracy of epicentral locations within the first 5-10 hrs following an earthquake in the SFBA is judged to be of the order of ± 5 km. How well can losses be interpolated from the contours shown? A number of tests were run to determine the smoothness of the loss data along profiles. An example is shown in figure 4. An east-west profile of losses has been computed across the SFBA. Earthquakes with I_o=VIII were assumed to occur at 2-km intervals along the profile. Examination of figure 4 shows that the data are quite smooth and can easily be interpolated from the contours, certainly within the accuracy of the method.

It should be understood that the method outlined provides only a quick rough estimate of percent losses. In particular, caution should be used in applying the technique particularly with regard to the following:

1. Earthquakes involving surface faulting may have the point of highest intensity (I_o) at a location quite different from the instrumental location of the epicenter. An example of this occurred with respect to the 1971 San Fernando, Calif., earthquake. Thus, the highest intensity may be related to geologic effects. If this is not realized, the use of the technique outlined here will yield erroneous results.
2. Because of the situation discussed in (1) above, a reconnaissance inspection of the meizoseismal area is invaluable, particularly if surface faulting (or other very unusual geologic effects) are suspected.

3. While rough estimates of losses can be obtained without any field investigation of an earthquake, even a cursory field examination of the most heavily damaged area by experienced personnel when used in conjunction with the method outlined in this report will give greatly improved estimates.

4. For earthquakes with I_o of IX and X, the surface faulting is assumed to occur in the central portion of the SFBA along the Hayward and San Andreas faults. For earthquakes on the San Andreas fault that may occur near the north or south edges of the SFBA, in which faulting does not extend into the central portion of the SFBA, the estimates are likely to be greatly in error.

APPLICABILITY OF THE METHODOLOGY TO OTHER PARTS OF THE UNITED STATES

The method for making approximate loss estimates outlined in this report depends upon the results of a number of earlier studies, as already noted. The inventory techniques, the isoseismal maps, and the intensity-loss relationships were all developed for the San Francisco Bay area. In theory, the method could be applied anywhere, provided that approximations to the inventory of the area are possible, intensity data are available, and loss-intensity relationships can be developed. Practically, this method is probably most transferable to other parts of California where land-use and zoning practices are similar to the SFBA, building classes are similar, and intensity-attenuation relationships are similar.

Use of the technique in the midwestern part of the United States (the St. Louis area, for example) would require as a minimum: (1) consideration of brick dwellings, which are common in the area but which were omitted from the SFBA study because they make up less than 5 percent of the single-family dwellings in the SFBA, (2) use of different intensity-attenuation relationships than those used in California, (3) research on methods to develop inventory for buildings other than single-family dwellings, and (4) study of the building classification and intensity-loss relationships to determine the adequacy of the relationships used in this report.

Single-family dwellings perhaps are the simplest class of building for which losses can be estimated in various parts of the country.

United States census data together with statistical sampling of construction characteristics on a regional basis provide sufficient information for inventory and for development of intensity-loss relationships.

To summarize, the applicability of the methodology developed here to areas other than the nine-county San Francisco area will depend on the following:

Inventory - The method used to obtain inventory in this report is transferable (1) if the building classification remains valid, and (2) if the area in question used a land classification scheme similar to the one on the San Francisco area. Building design and construction practice in any area to which this methodology is to be transferred must be carefully evaluated.

Loss-ground shaking relationships - Loss-ground shaking relationships (M.M. intensity) will remain approximately the same <u>if</u> the building classification used here remains valid in the new area where the methodology is to be applied. In the Eastern United States, design and construction practice are, in some instances, different than in the present study area. Sound engineering judgment must be used to modify the loss-ground shaking relationships to take these differences in design and construction practice into account.

The Modified Mercalli scale as a measure of ground shaking - More quantitative measures of ground shaking derived from records of strong ground motion are still quite rare outside of California.

Despite its flaws and limitations, the M.M. scale provides a measure of ground shaking that is widely available for historical earthquakes that have occurred throughout the United States.

Although the damage tables and curves in this report refer to California construction and are based on California seismic experience, they may prove of interest to those attempting estimates for other areas, but probably cannot be used for reliable estimates for such areas.

From this discussion it is evident that a great deal of work and research is needed. Just a few items are listed.

For areas other than California:

1. Loss-intensity relationships;
2. Intensity-attenuation relationships;
3. Catalog of construction practices;
4. Inventories (number and value) of 1-4 family residences by construction class;
5. Inventories of high-rise and nonresidential buildings by construction class and value.

For all areas:

1. Methodologies for estimating damages to 1- to 4-family masonry dwellings;
2. Methods for estimating damages from ground failure (landslide, liquefaction, subsidence);
3. Methods for estimating damages from tsunamis;
4. Methods for estimating damages to lifelines, transportation facilities (roads, bridges, railroads), and public utility facilities.

CONCLUSIONS

The following general conclusions were obtained from this study:

1. Losses for some building classes are about the same for earthquakes with I_o=IX on the Hayward fault and for earthquakes with I_o=X on the San Andreas fault.
2. Losses for earthquakes with I_o in the range from VI to VIII are greatest for earthquakes that have their epicenters in or near the south end of San Francisco Bay.
3. Subclass 4HD (buildings over four stories in height and having (a) a partial or complete load-carrying system of precast concrete; and/or (b) reinforced concrete lift slab floors and/or roofs; and (c) otherwise qualifying for classes IV-A, B, or C) has the greatest percent loss of any building subclass for any large earthquake in the SFBA. The percent loss is approximately 29 percent of replacement value.
4. A rapid method of estimating building losses associated with ground shaking has been outlined and demonstrated for the San Francisco Bay area (SFBA).
5. The method depends upon a building classification, inventory, and ground shaking (intensity) data developed in previous studies.
6. Care must be taken in using the method in earthquakes where surface faulting or large-scale ground failures are suspected. Surface faulting and other geological effects may result in the center of damage being located at a very different location from the instrumentally determined epicenter.

7. Even a brief field examination by experienced personnel of the most heavily damaged area of an earthquake, together with the application of the technique outlined in this report will greatly improve the resulting loss estimates over those loss estimates obtained without any field examination.

8. The technique is generally applicable anywhere but it depends upon construction practice, development of inventory, attenuation of ground shaking, and loss-intensity relationships in the area where it is applied.

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APPENDIX A

Table A1.--Building classification used in this study

Class I-Wood frame

Class I-A

1. Wood frame and frame stucco dwellings regardless of area and height.

2. Wood frame and frame stucco buildings, other than dwellings, which do not exceed 3 stories in height and do not exceed 3,000 sq ft in ground floor area.

3. Wood frame and frame stucco habitational structures which do not exceed 3 stories in height regardless of area.

Class I-B

Wood frame and frame stucco buildings not qualifying under Class I-A.

Class II-All-metal buildings

Class II-A

One story all-metal buildings which have a floor area not exceeding 20,000 sq ft.

Class II-B

All-metal buildings not qualifying under Class II-A.

Class III-Steel frame buildings

Class III-A

Buildings having a complete steel frame with all loads carried by the steel frame. Floors and roofs shall be of poured-in-place reinforced concrete, or of concrete fill on metal decking welded to the steel frame (open web steel joists excluded). Exterior walls shall be of poured-in-place reinforced concrete or of reinforced unit masonry placed within the frame. Buildings shall have a least width to height above ground (or above any setback) ratio of not exceeding one to four. Not qualifying are buildings having column-free areas greater than 2,500 sq ft (such as auditoriums, theaters, public halls, etc.).

Table A1.--Building classification used in this study--Continued

Class III-Steel frame buildings

Class III-B

Buildings having a complete steel frame with all loads carried by the steel frame. Floors and roofs shall be of poured-in-place reinforced concrete or metal, or any combination thereof, except that roofs on buildings over three stories may be of any material. Exterior and interior walls may be of any non-load carrying material.

Class III-C

Buildings having some of the favorable characteristics of Class III-A but otherwise falling into Class III-B.

Class III-D

Buildings having a complete steel frame with floors and roofs of any material and with walls of any non-load bearing materials.

Class IV-Reinforced concrete, combined reinforced concrete and structural steel frame

Note: Class IV-A, B, and C buildings shall have all vertical loads carried by a structural system consisting of one or a combination of the following: (a) poured-in-place reinforced concrete frame, (b) poured-in-place reinforced concrete bearing walls, (c) partial structural steel frame with (a) and/or (b). Floors and roof shall be of poured-in-place reinforced concrete, except that materials other than reinforced concrete may be used for the roofs on buildings over 3 stories.

Class IV-A

Buildings having a structural system as defined by the note (above) with poured-in-place reinforced concrete exterior walls or reinforced unit masonry exterior walls placed within the frame. Buildings shall have at least width to height above ground (or above any setback) ratio of not exceeding one to three. Not qualifying are buildings having column-free areas greater than 2,500 sq ft (such as auditoriums, theaters, public halls, and so forth).

Class IV-B

Buildings having a structural system as defined by the note (above) with exterior and interior non-bearing walls of any material.

Table A1.--Building classification used in this study--Continued

Class IV-Reinforced concrete, combined reinforced concrete and structural steel frame

Class IV-C

Buildings having some of the favorable characteristics of Class IV-A but otherwise falling into Class IV-B.

Class IV-D

Buildings having (a) a partial or complete load carrying system of precast concrete, and/or (b) reinforced concrete lift slab floors and/or roofs, and (c) otherwise qualifying for Classes IV-A, B, or C.

Class IV-E

Buildings having a complete reinforced concrete frame, or a complete frame of combined reinforced concrete and structural steel. Floors and roofs may be of any material while walls may be of any non-load bearing material.

Class V-Mixed construction

Class V-A

1. Dwellings, not over two stories in height, constructed of poured-in-place reinforced concrete, with roofs and second floors of wood frame.

2. Dwellings, not over two stories in height, constructed of adequately reinforced brick or hollow concrete block masonry, with roofs and floors of wood.

Class V-B

One story buildings having superior earthquake damage control features including exterior walls of (a) poured-in-place reinforced concrete, and/or (b) precast reinforced concrete, and/or (c) reinforced brick masonry or reinforced concrete brick masonry, and/or (d) reinforced hollow concrete block masonry. Roofs and supported floors shall be of wood or metal diaphragm assemblies. Interior bearing walls shall be of wood frame or any one or a combination of the aforementioned wall materials.

Class V-C

One story buildings having construction materials listed for Class V-B, but with ordinary earthquake damage control features.

Class V-D

1. Buildings having reinforced concrete load-bearing walls with floors and roofs of wood and not qualifying for Class IV-E.

2. Buildings of any height having Class V-B materials of construction, including wall reinforcement; also included are buildings with roofs and supported floors of reinforced concrete (precast or otherwise) not qualifying for Class IV.

Class V-E

Buildings having unreinforced solid-unit masonry of unreinforced brick, unreinforced concrete brick, unreinforced stone, or unreinforced concrete, where the loads are carried in whole or in part by the walls and partitions. Interior partitions may be wood frame or any of the aforementioned materials. Roofs and floors may be of any material. Not qualifying are buildings with nonreinforced load-carrying walls of hollow tile or other hollow-unit masonry, adobe, or cavity construction.

Class V-F

1. Buildings having load-carrying walls of hollow tile or other hollow unit masonry construction, adobe, and cavity wall construction.

2. Any building not covered by any other class.

(Classes VI-A, B, C, D, and E-Earthquake resistive construction

Any building or structure with any combination of materials and with earthquake damage-control features equivalent to those found in Classes I through V buildings. Alternatively, a qualifying building or structure may be classed as any class from I through V (instead of VI-A, B, C, D, or E) if the construction resembles that described for one of these classes and if the qualifying building or structure has an equivalent damageability.

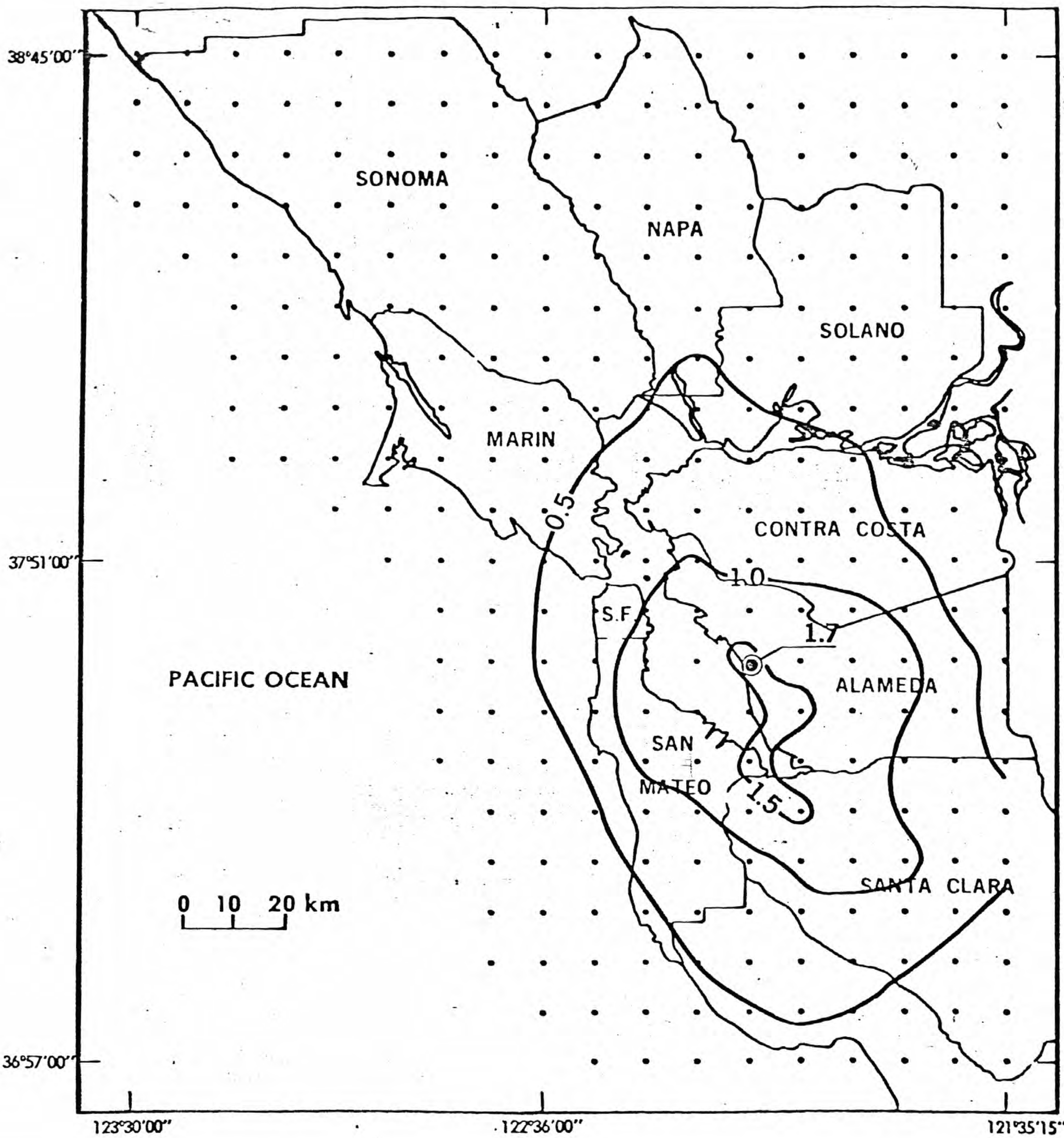

Figure A1.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LB for an earthquake with maximum intensity I_o=VI.

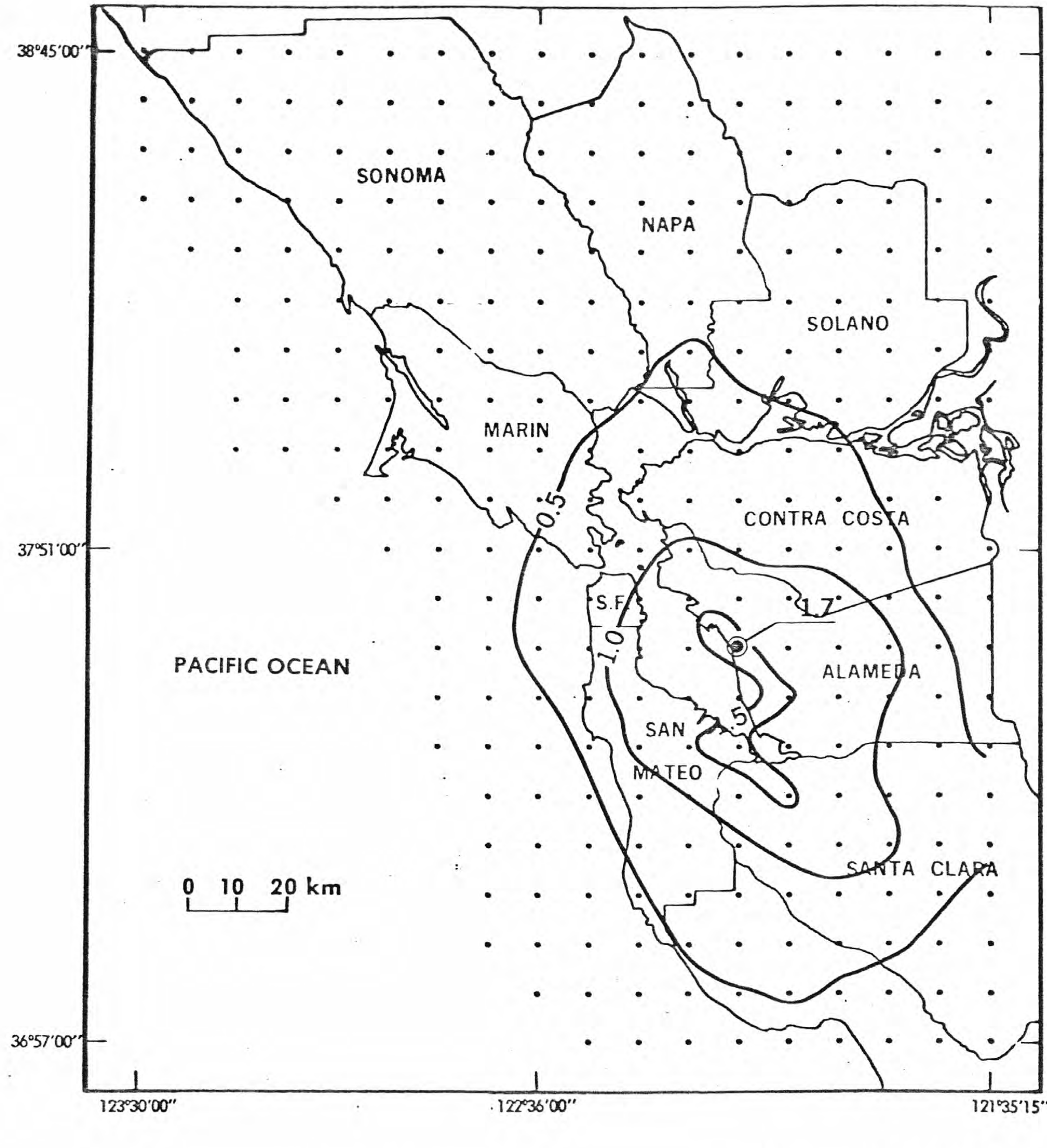

Figure A2.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LD for an earthquake with maximum intensity I_o=VI.

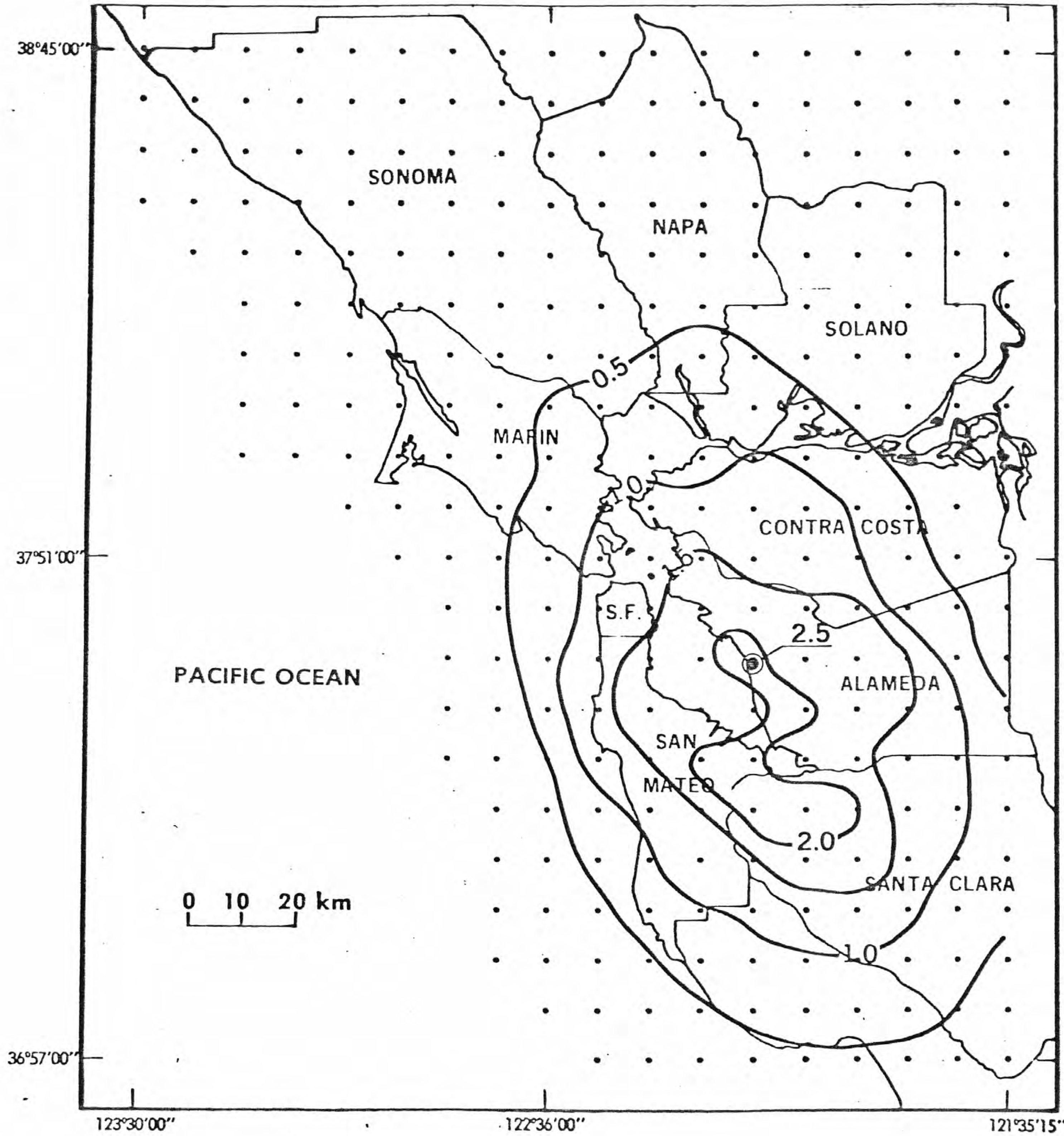

Figure A3.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LB for an earthquake with maximum intensity I_o=VI.

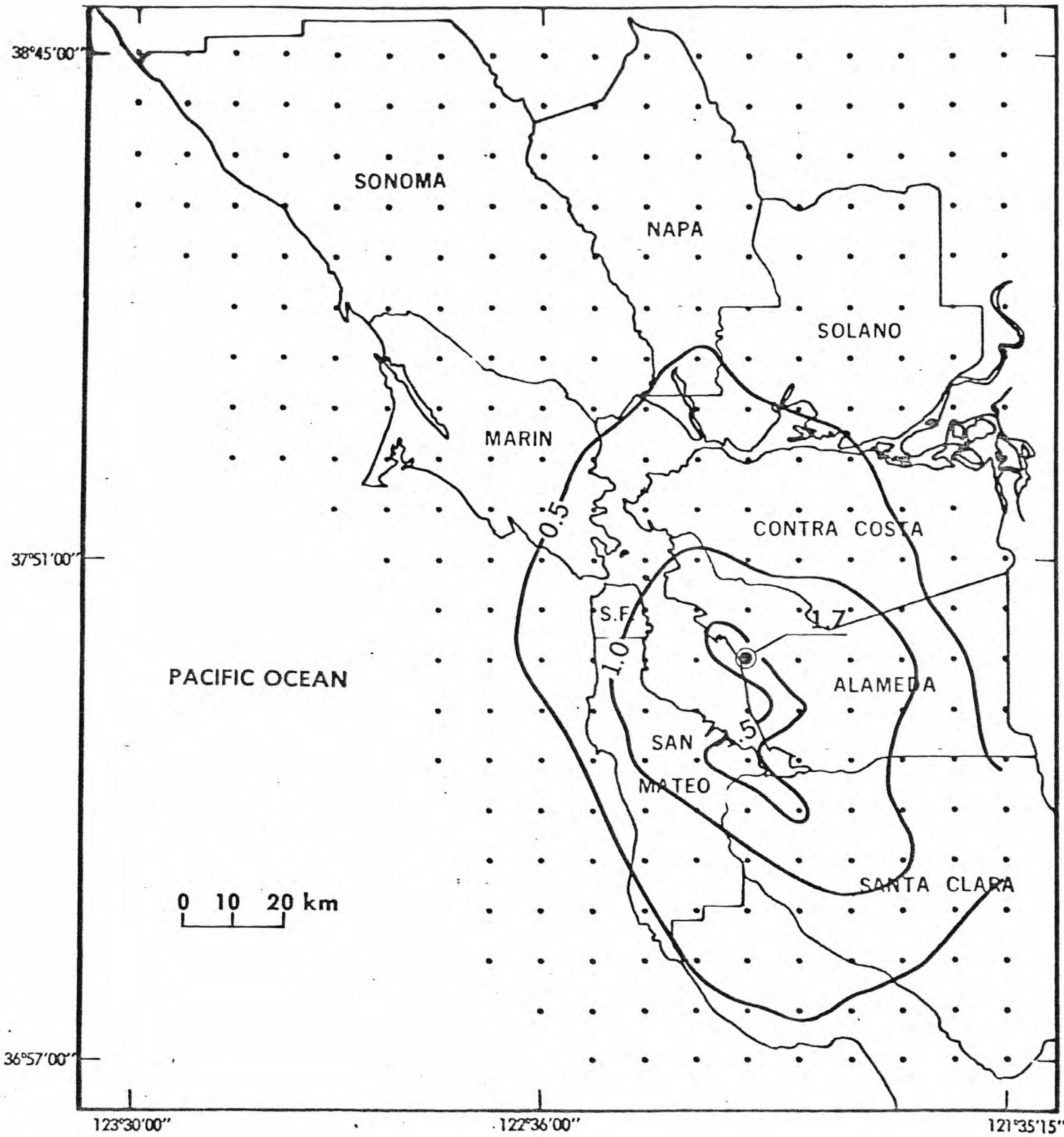

Figure A4.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LC for an earthquake with maximum intensity I_o=VI.

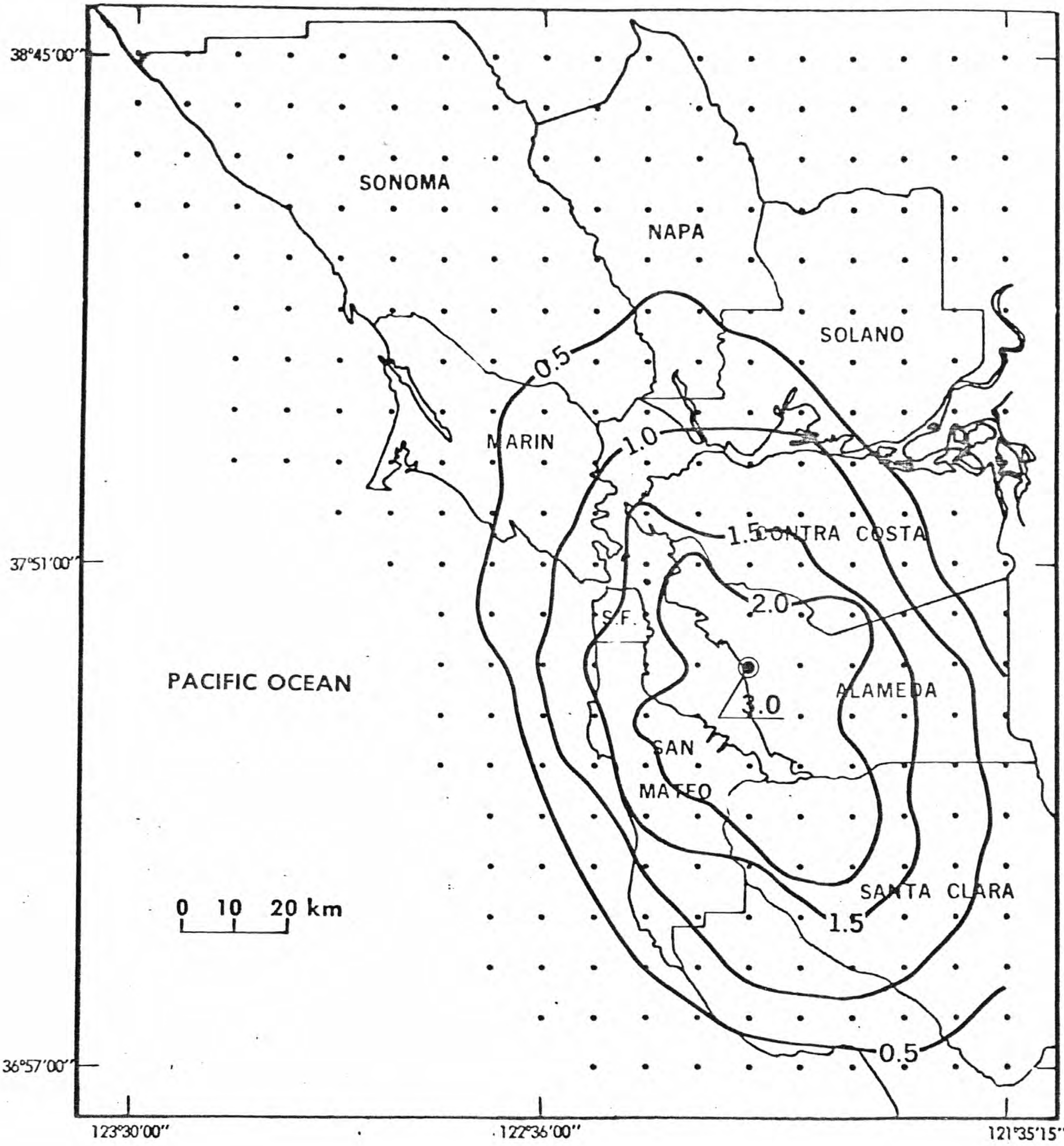

Figure A5.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LD for an earthquake with maximum intensity I_o=VI.

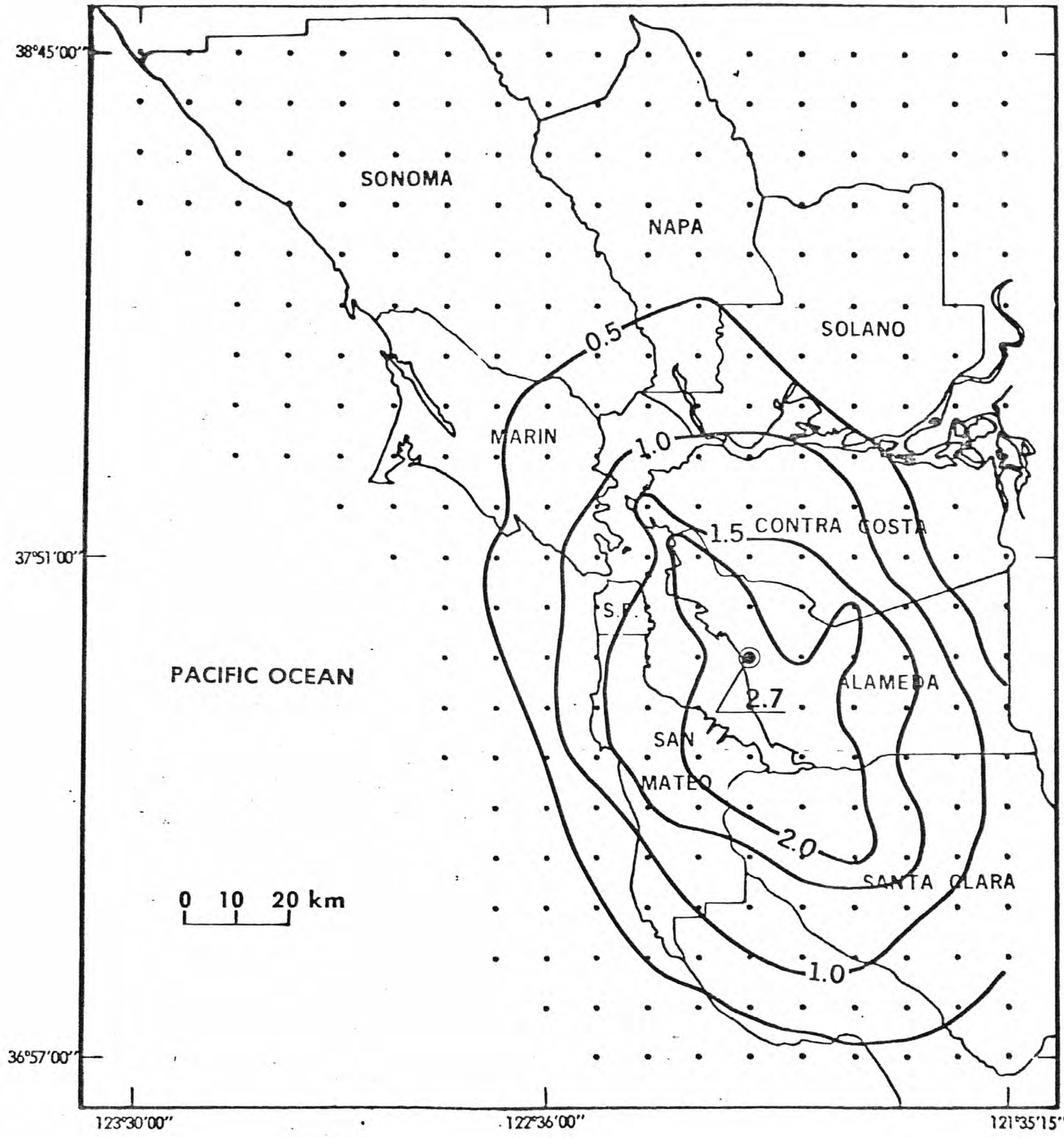

Figure A6.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LE for an earthquake with maximum intensity I_o=VI.

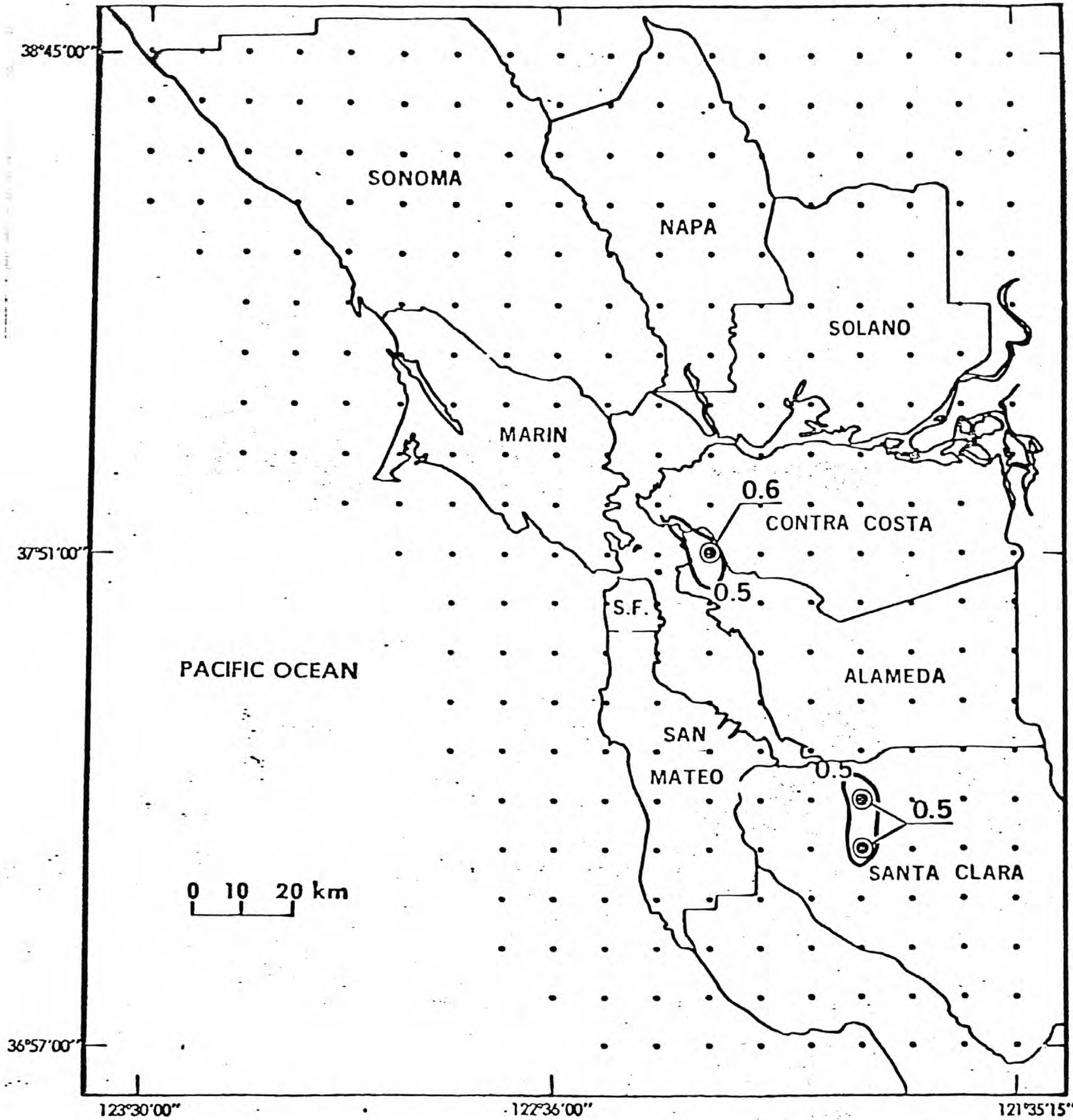

Figure A7.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HB for an earthquake with maximum intensity I_o=VI.

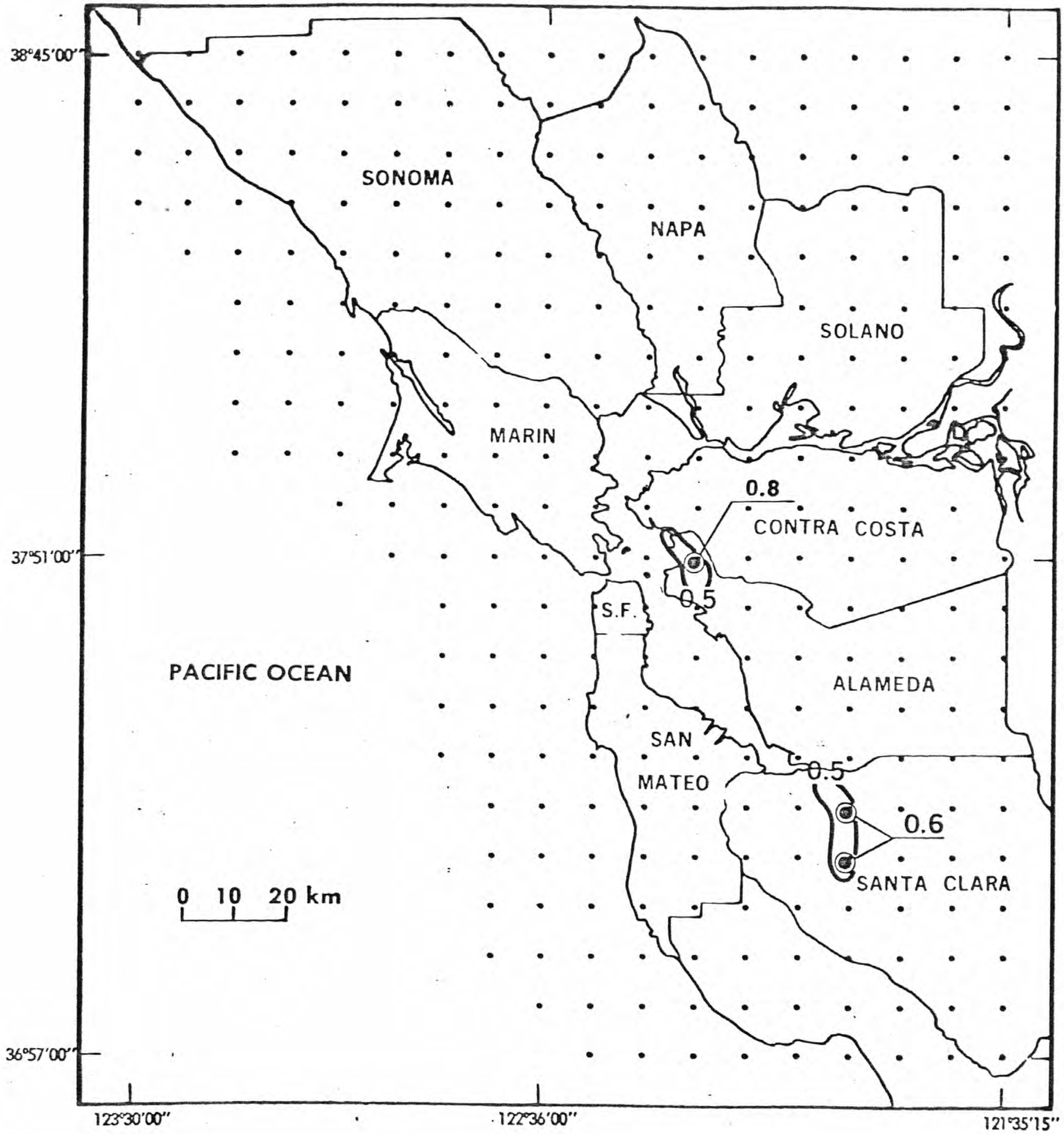

Figure A8.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HD for an earthquake with maximum intensity I_o=VI.

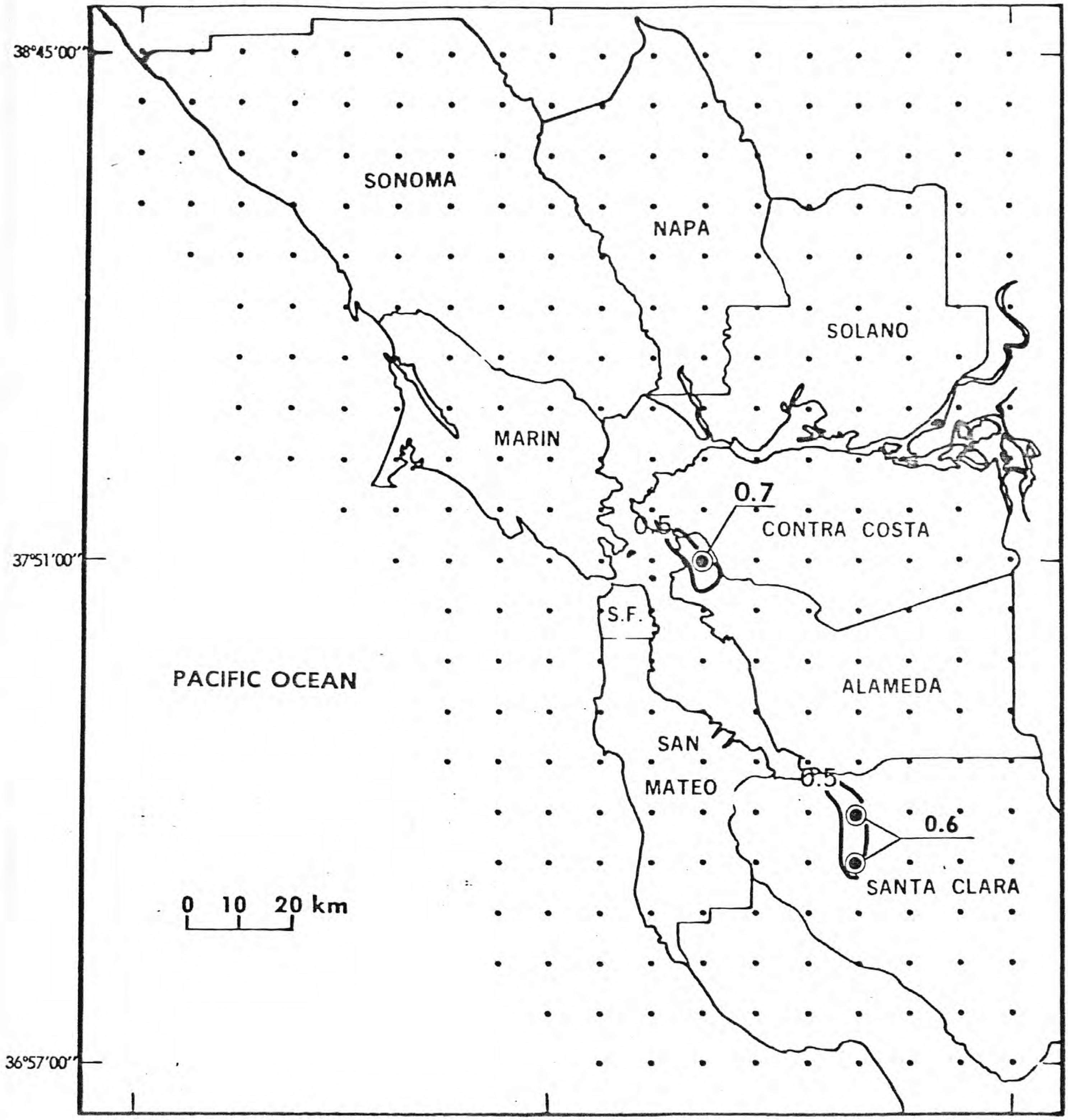

Figure A9.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HE for an earthquake with maximum intensity I_o=VI.

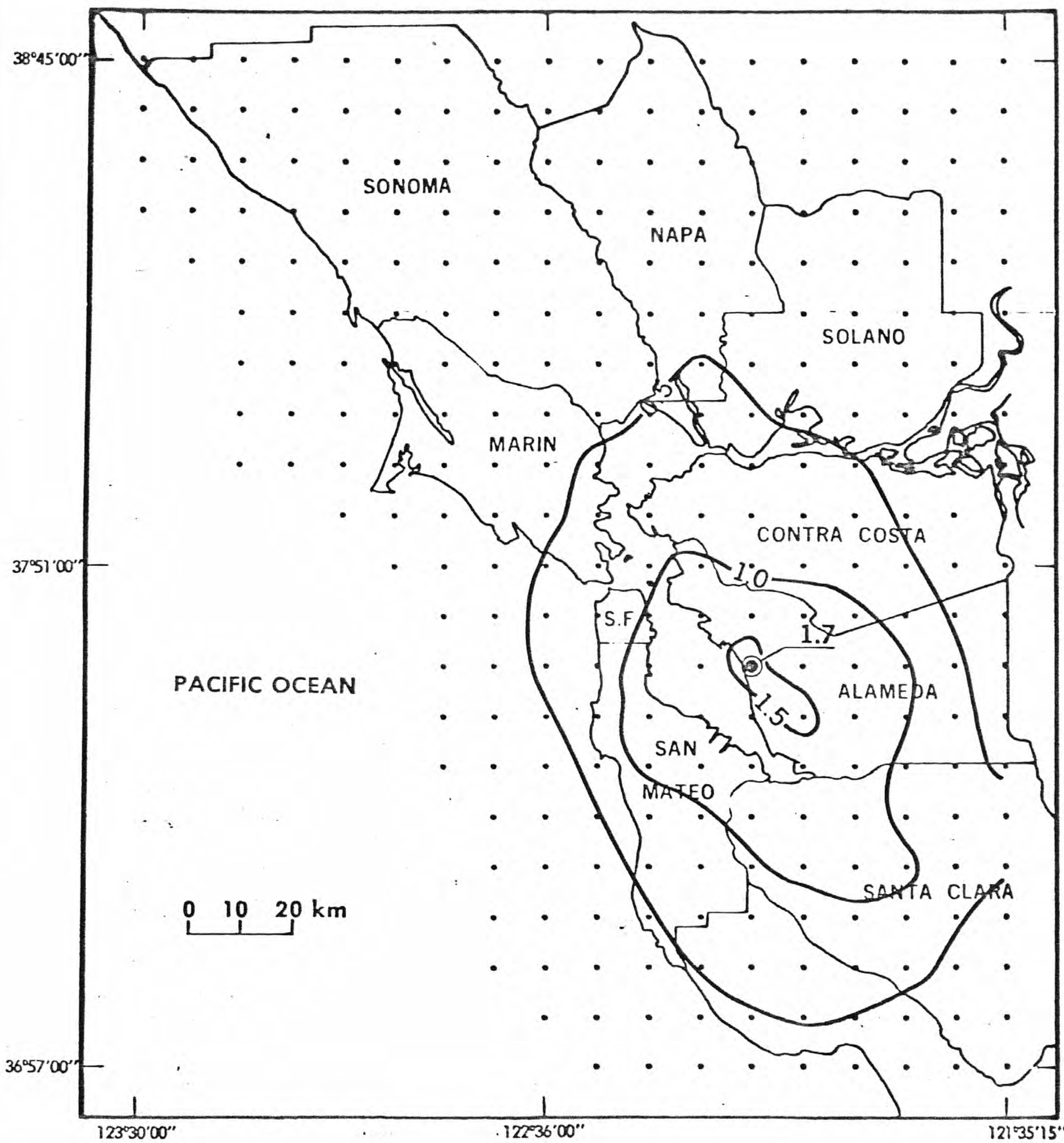

Figure A10.--Percent losses (contours) in the San Francisco Bay area for building subclass 5C for an earthquake with maximum intensity I_o=VI.

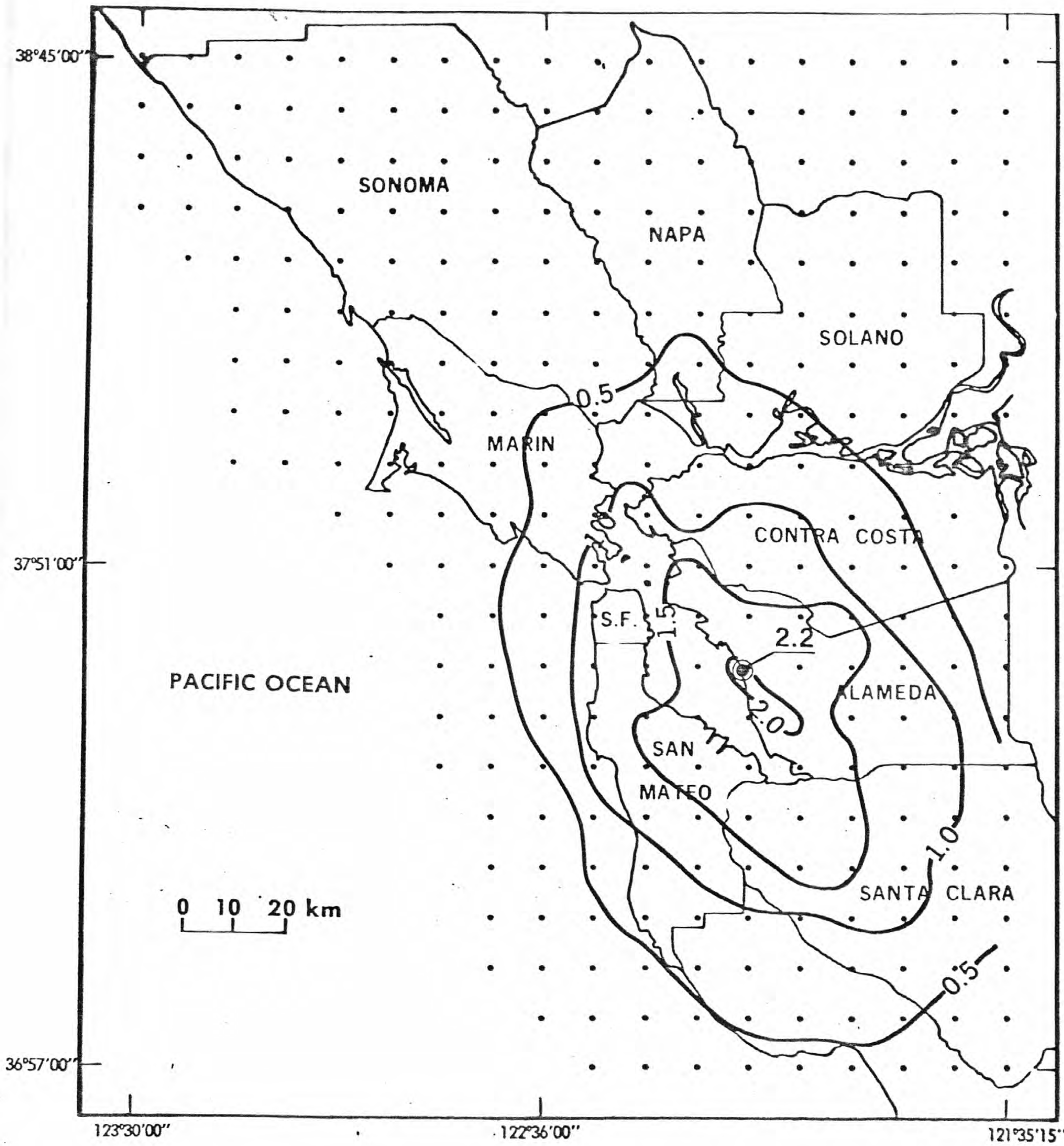

Figure A11.--Percent losses (contours) in the San Francisco Bay area for building subclass 5D for an earthquake with maximum intensity I_o=VI.

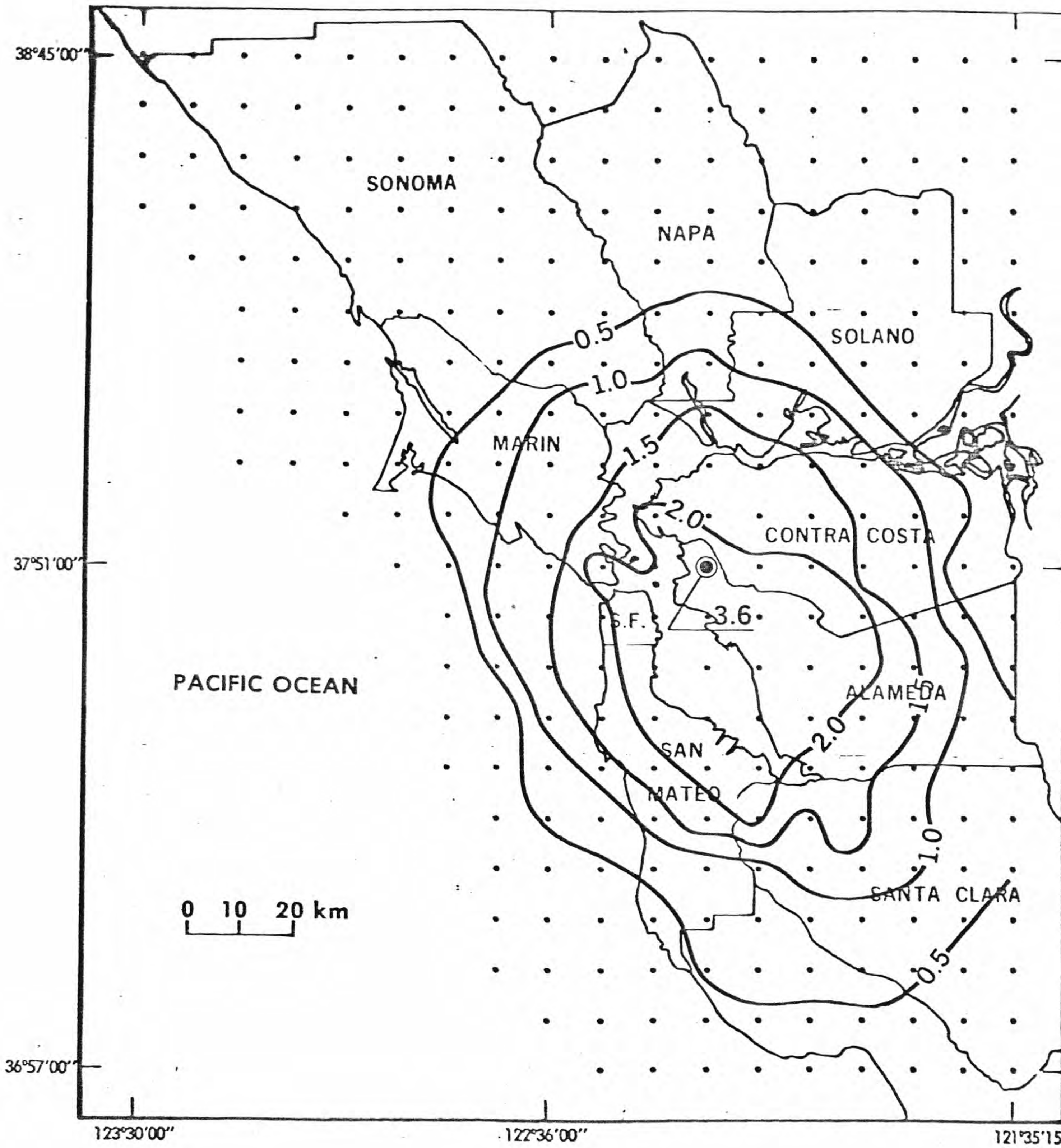

Figure A12.--Percent losses (contours) in the San Francisco Bay area for building subclass 5E for an earthquake with maximum intensity I_o=VI.

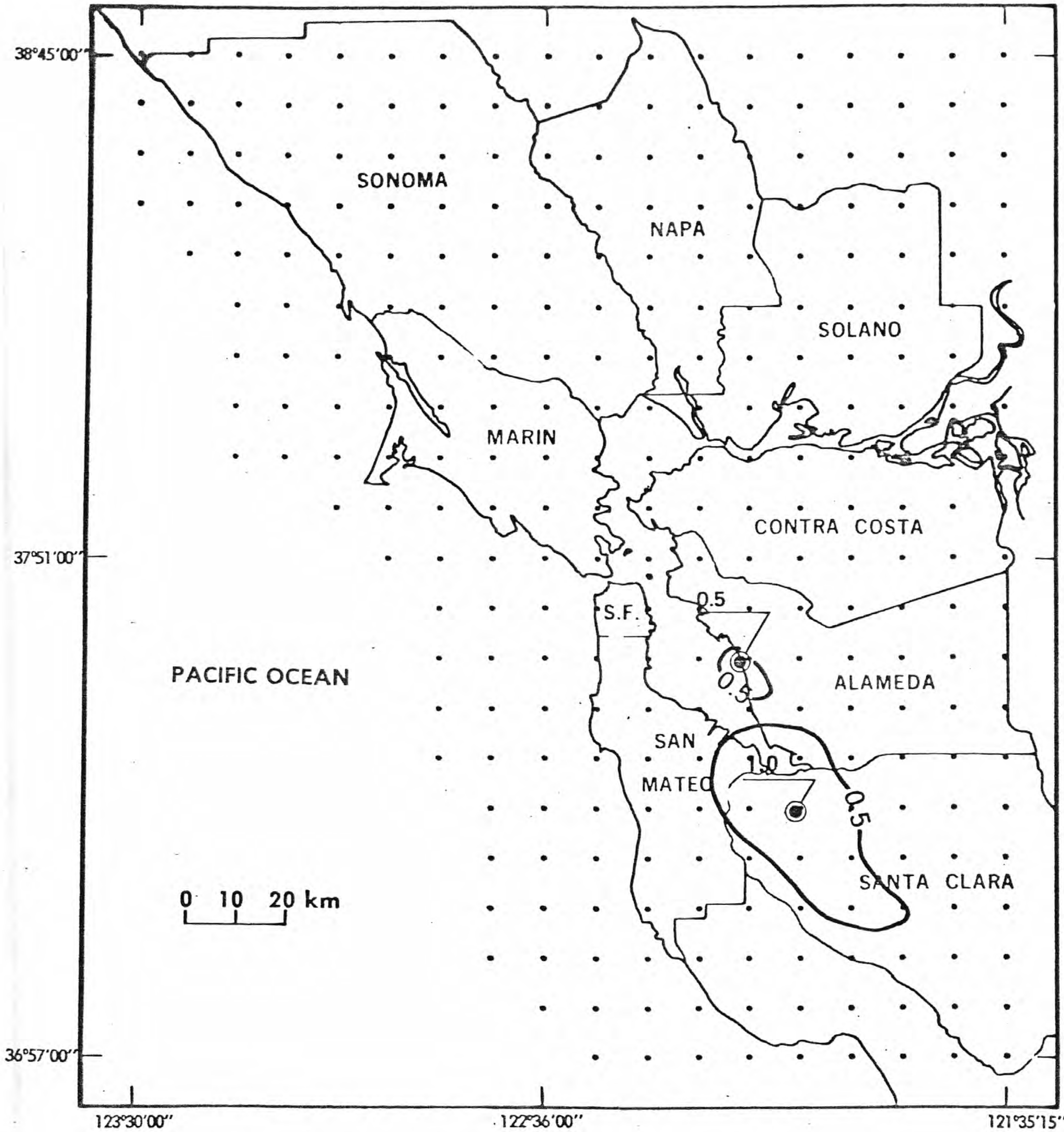

Figure A13.--Percent losses (contours) in the San Francisco Bay area for building subclass 2A for an earthquake with maximum intensity I_o=VII.

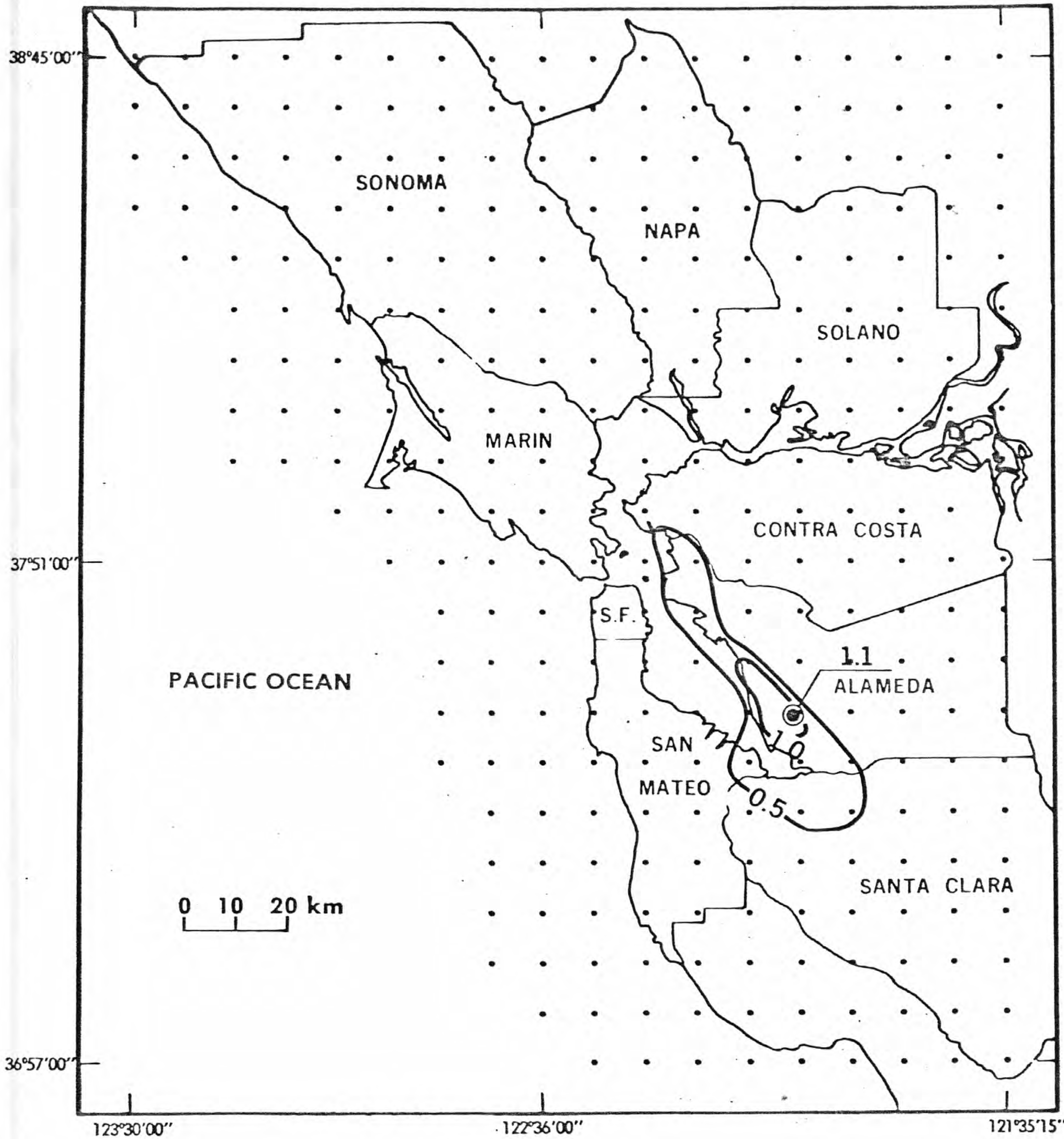

Figure A14.--Percent losses (contours) in the San Francisco Bay area for building subclass 2B for an earthquake with maximum intensity I_o=VII.

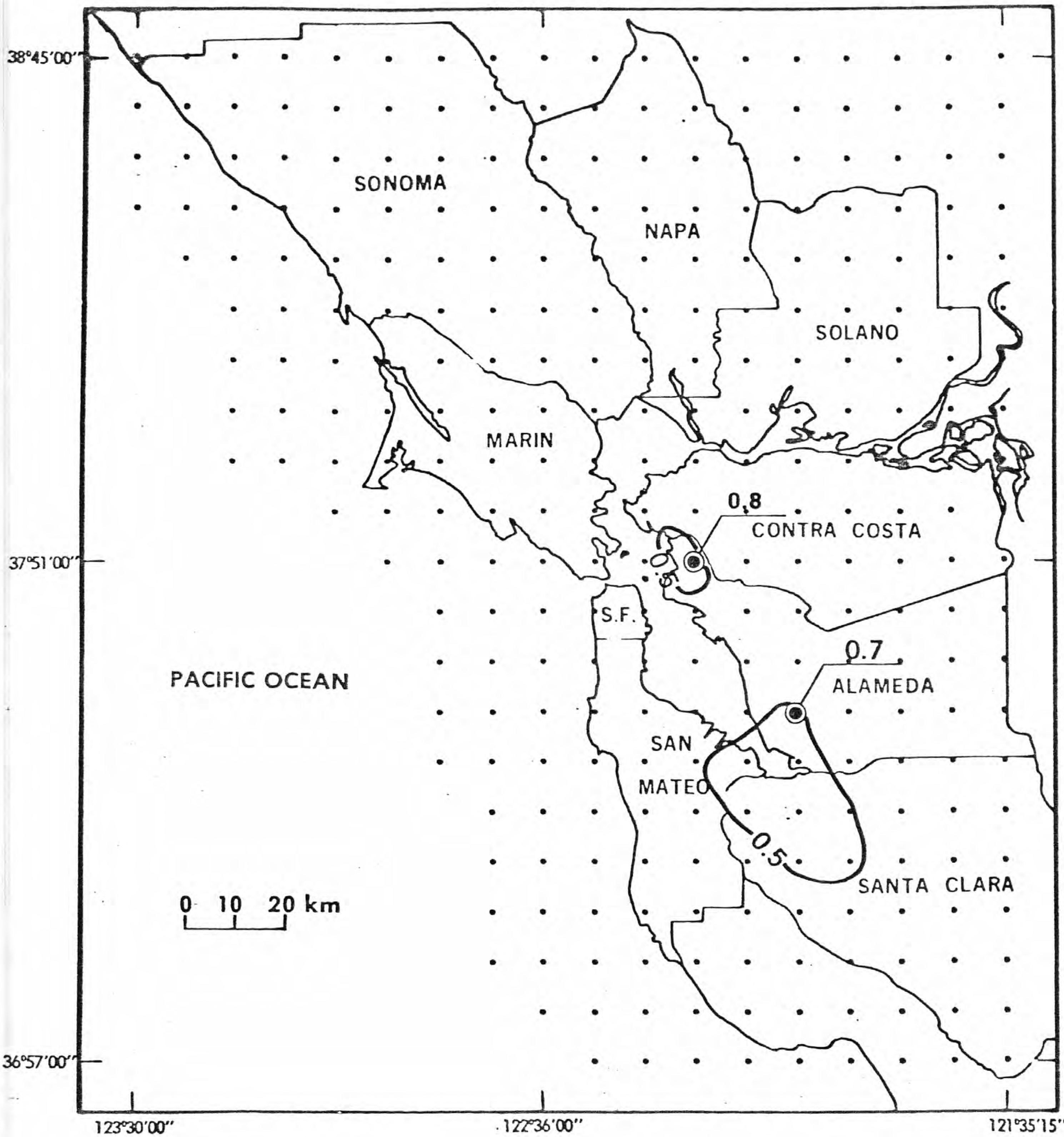

Figure 215.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LA for an earthquake with maximum intensity I_o=VII.

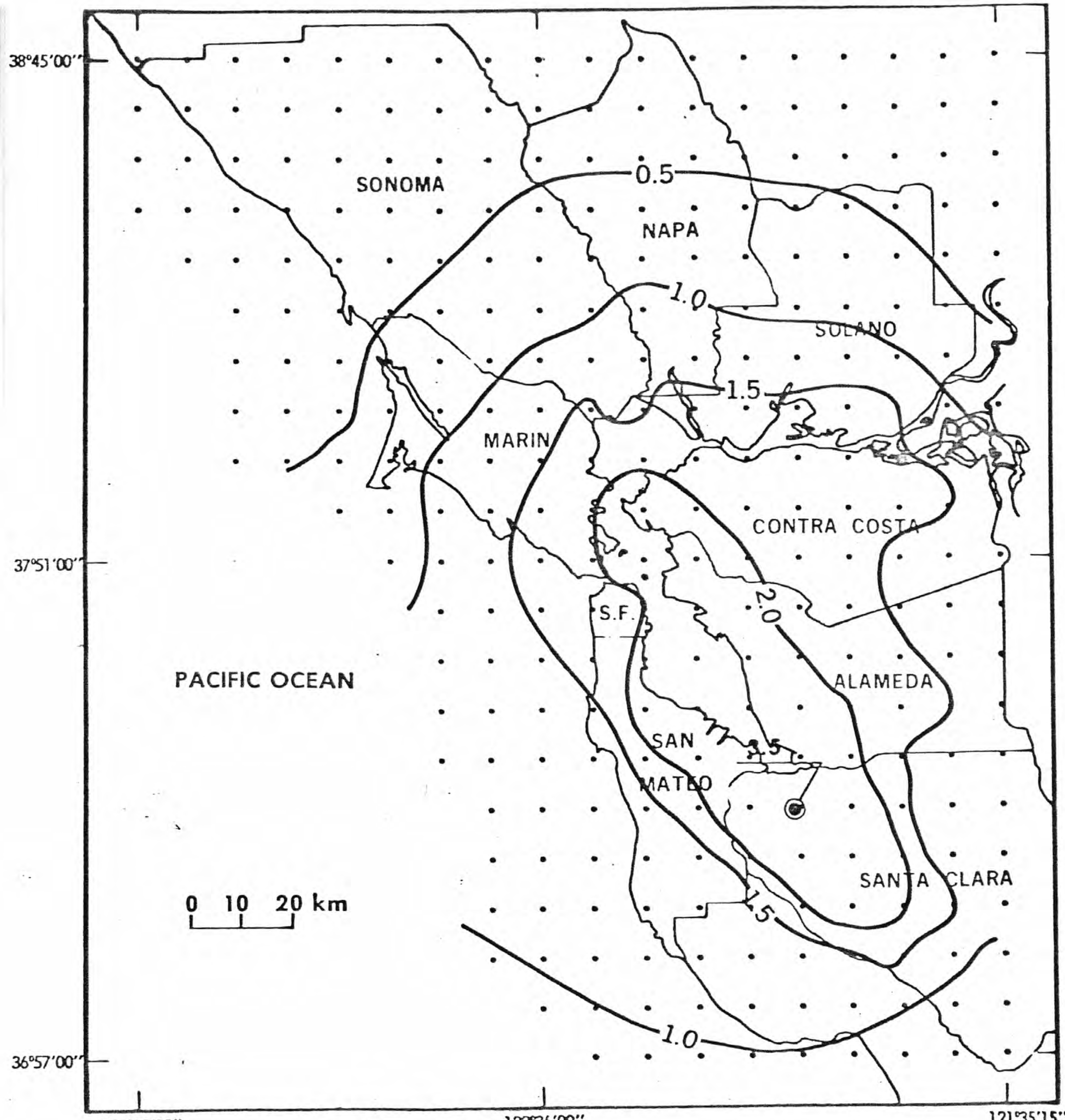

Figure A16.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LB for an earthquake with maximum intensity I_o=VII.

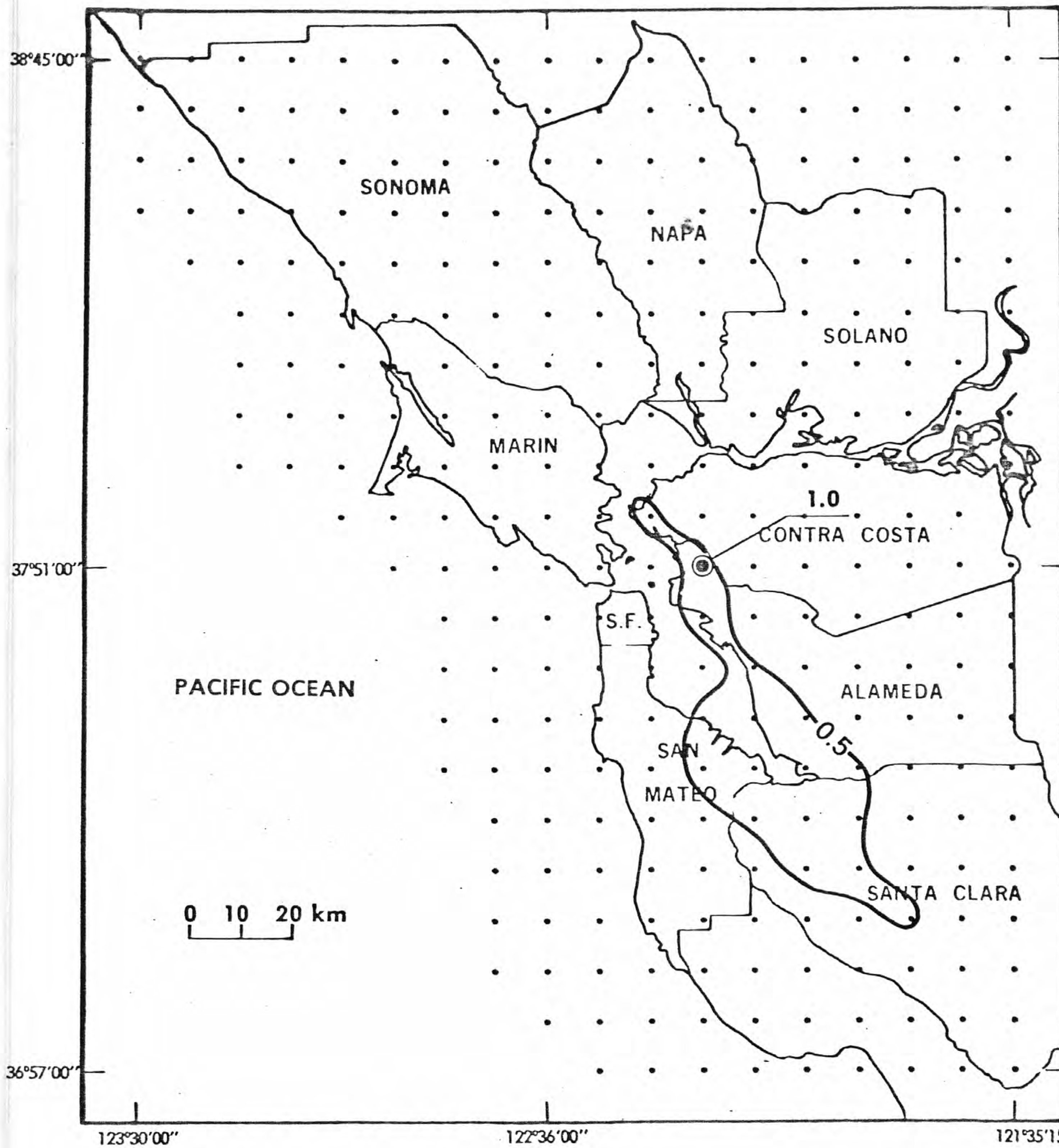

Figure A17.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LC for an earthquake with maximum intensity I_o=VII.

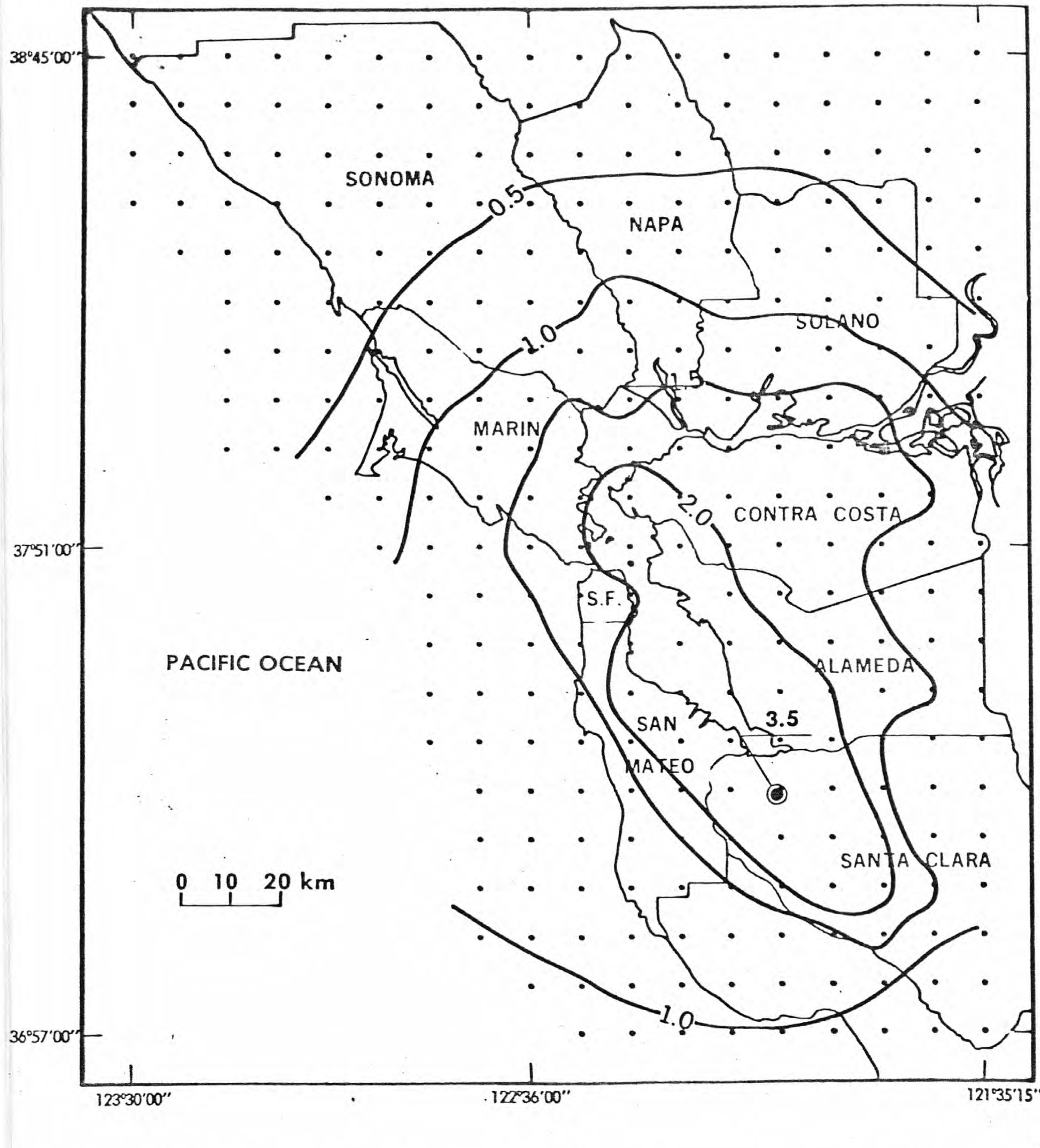

Figure A18.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LD for an earthquake with maximum intensity I_o=VII.

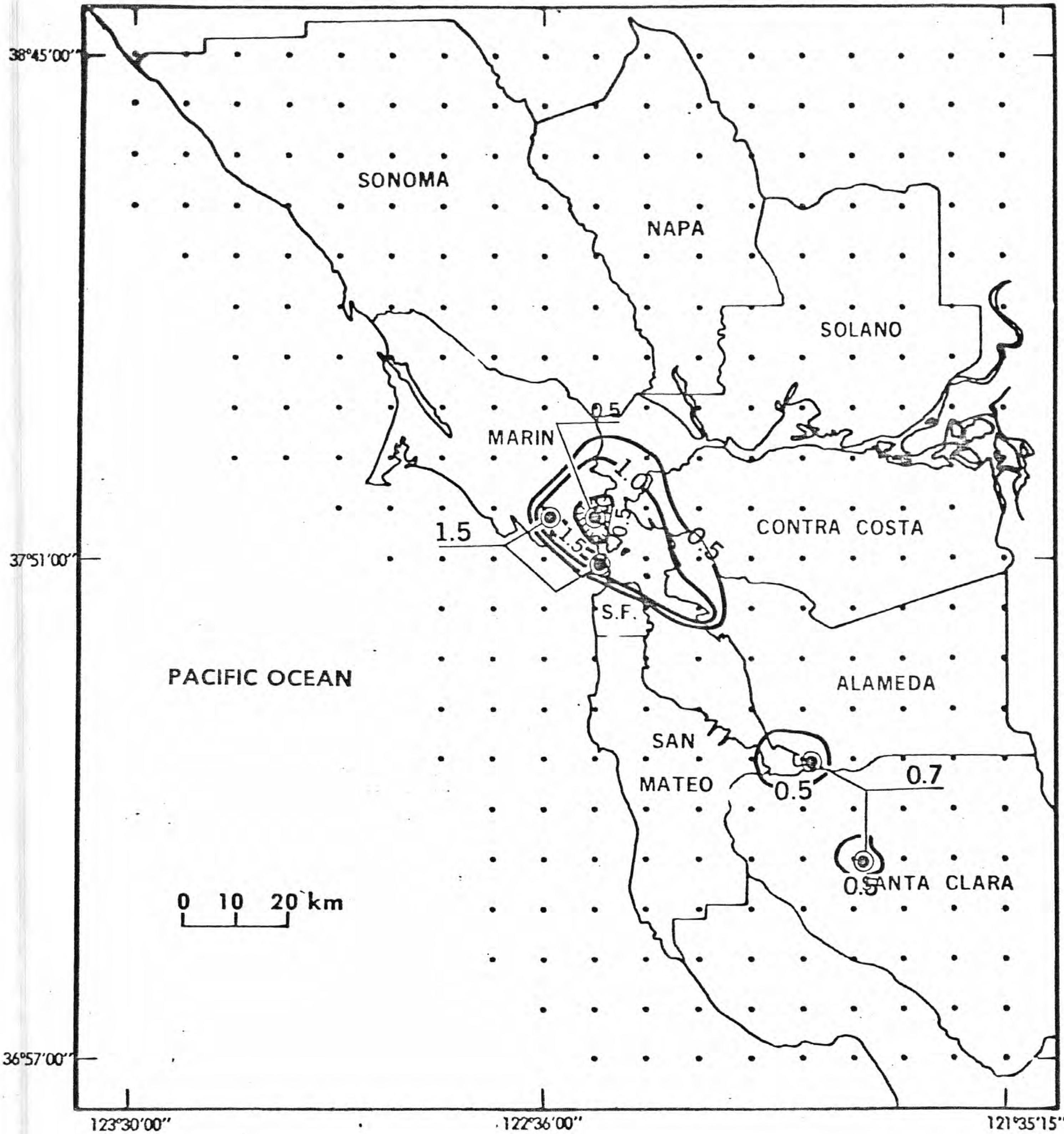

Figure A19.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HB for an earthquake with maximum intensity I_o=VII.

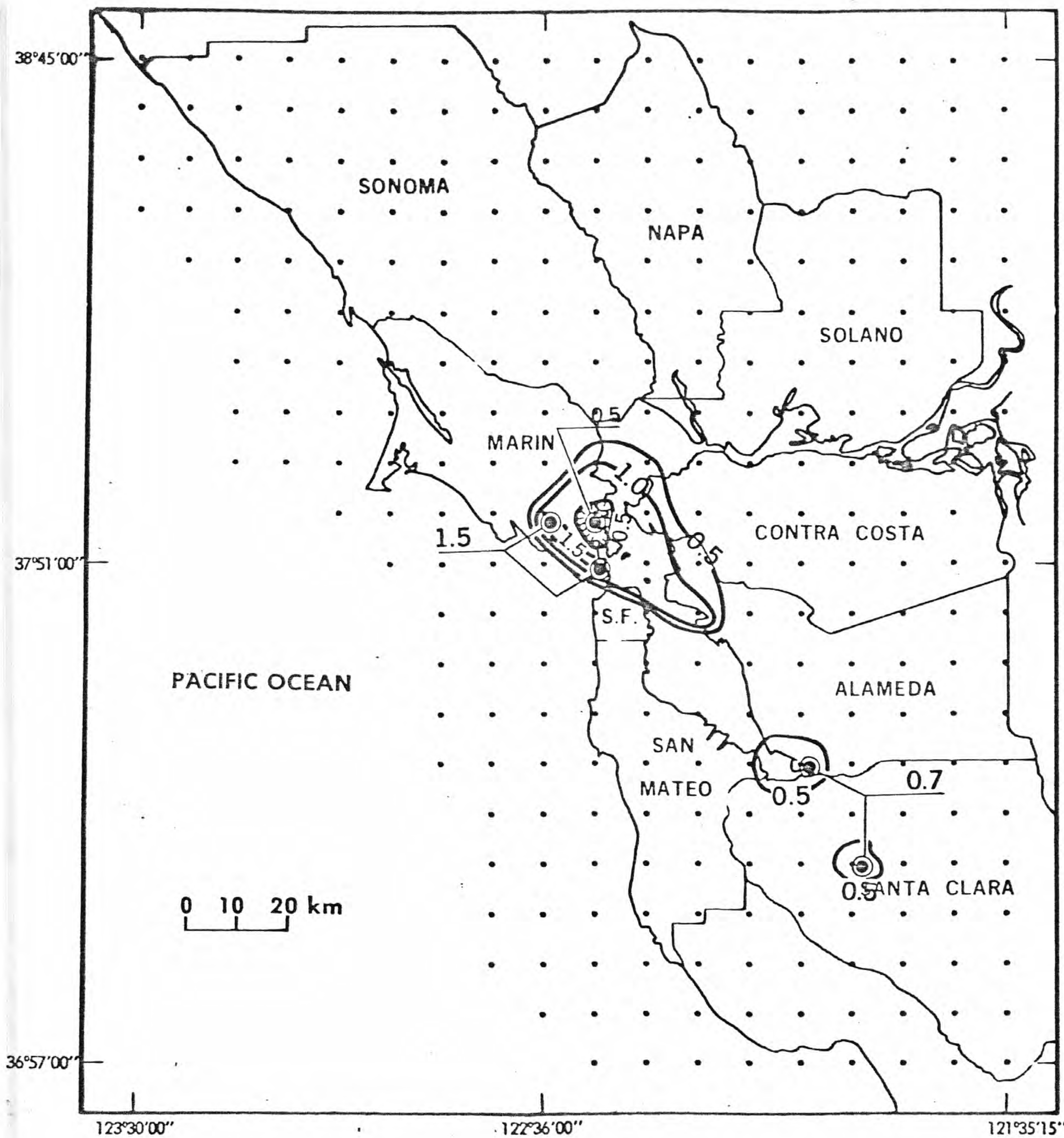

Figure A20.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HD for an earthquake with maximum intensity I_o=VII.

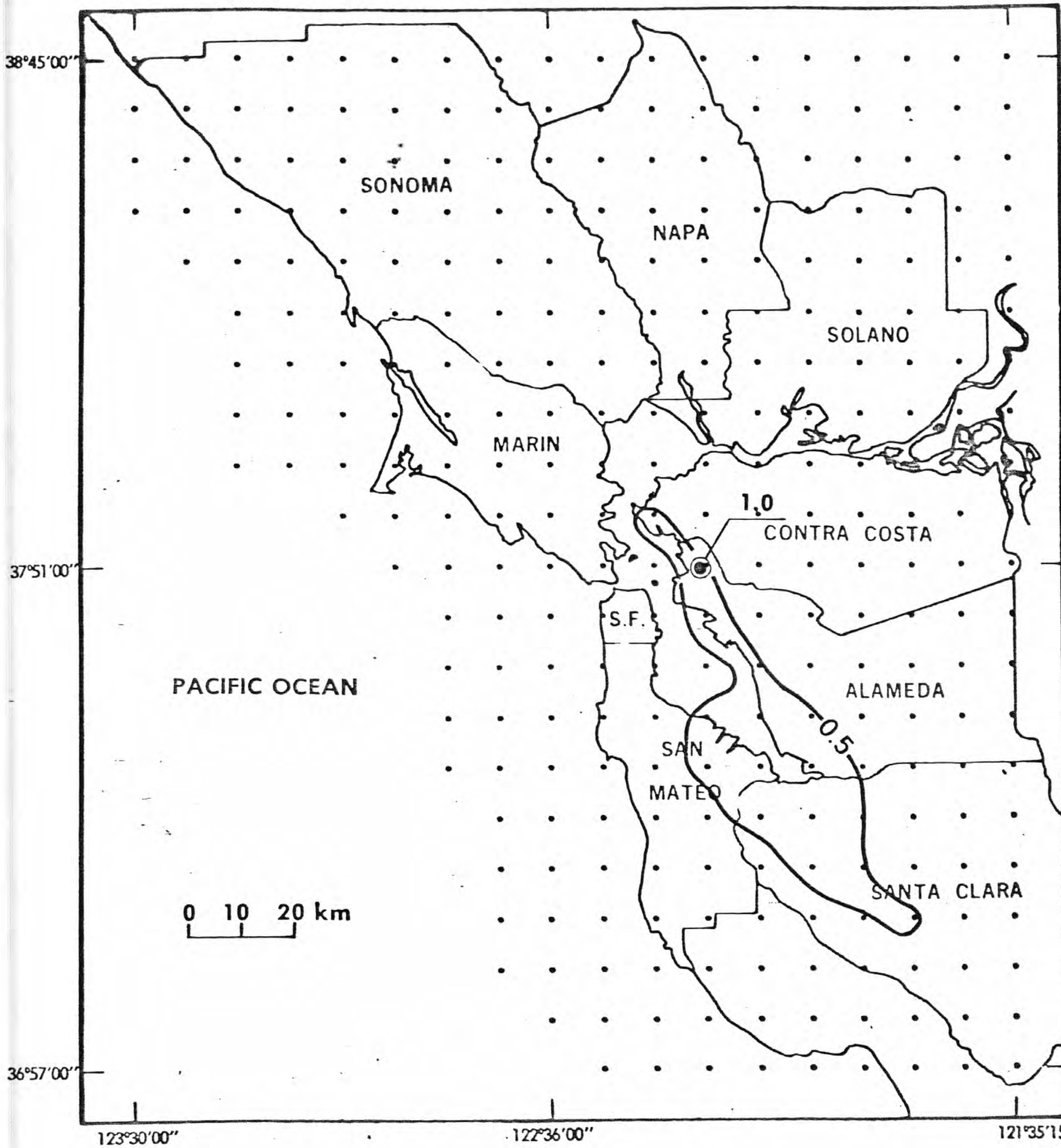

Figure A21.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LA for an earthquake with maximum intensity I_o=VII.

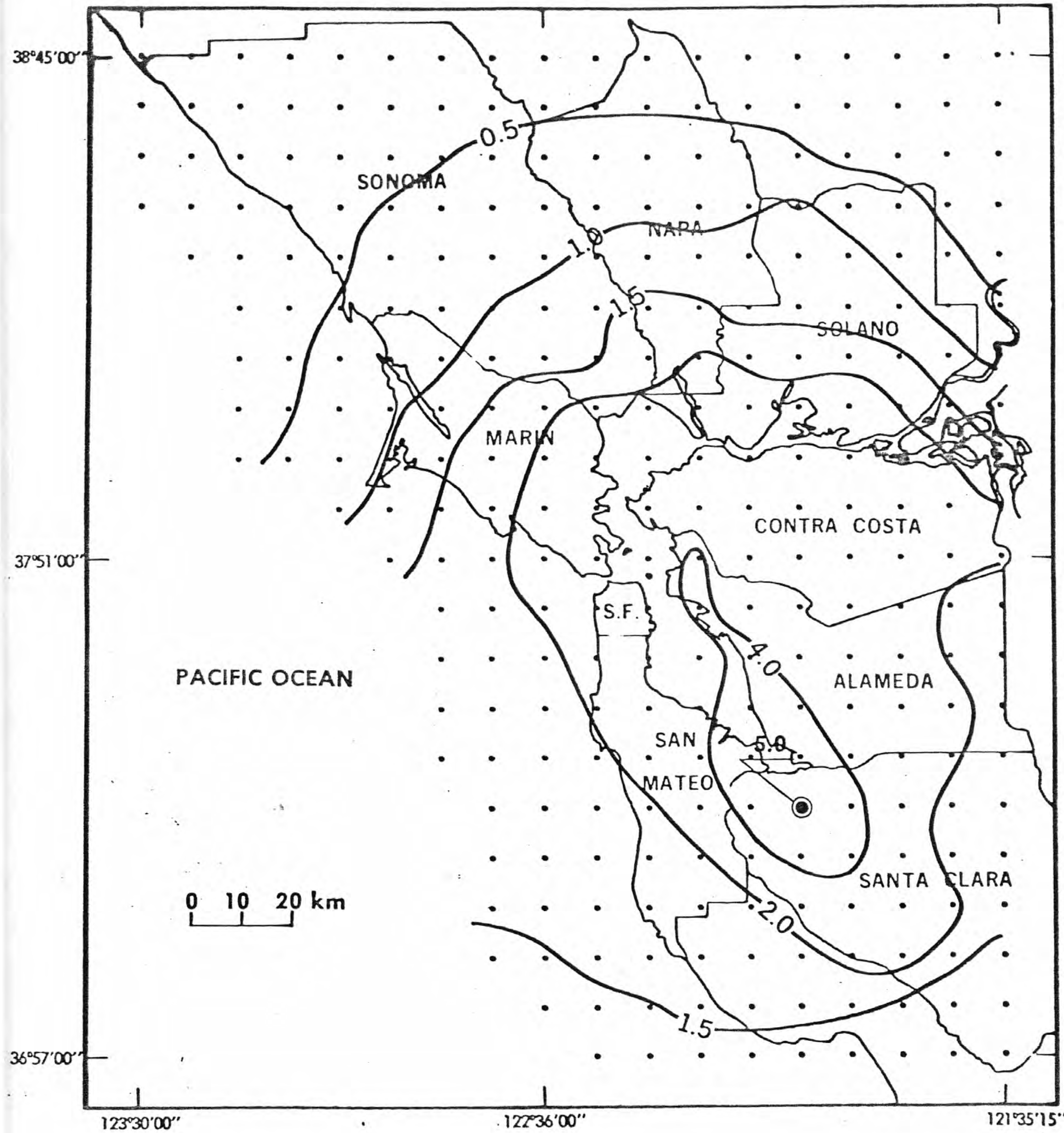

Figure A22.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LB for an earthquake with maximum intensity I_o=VII.

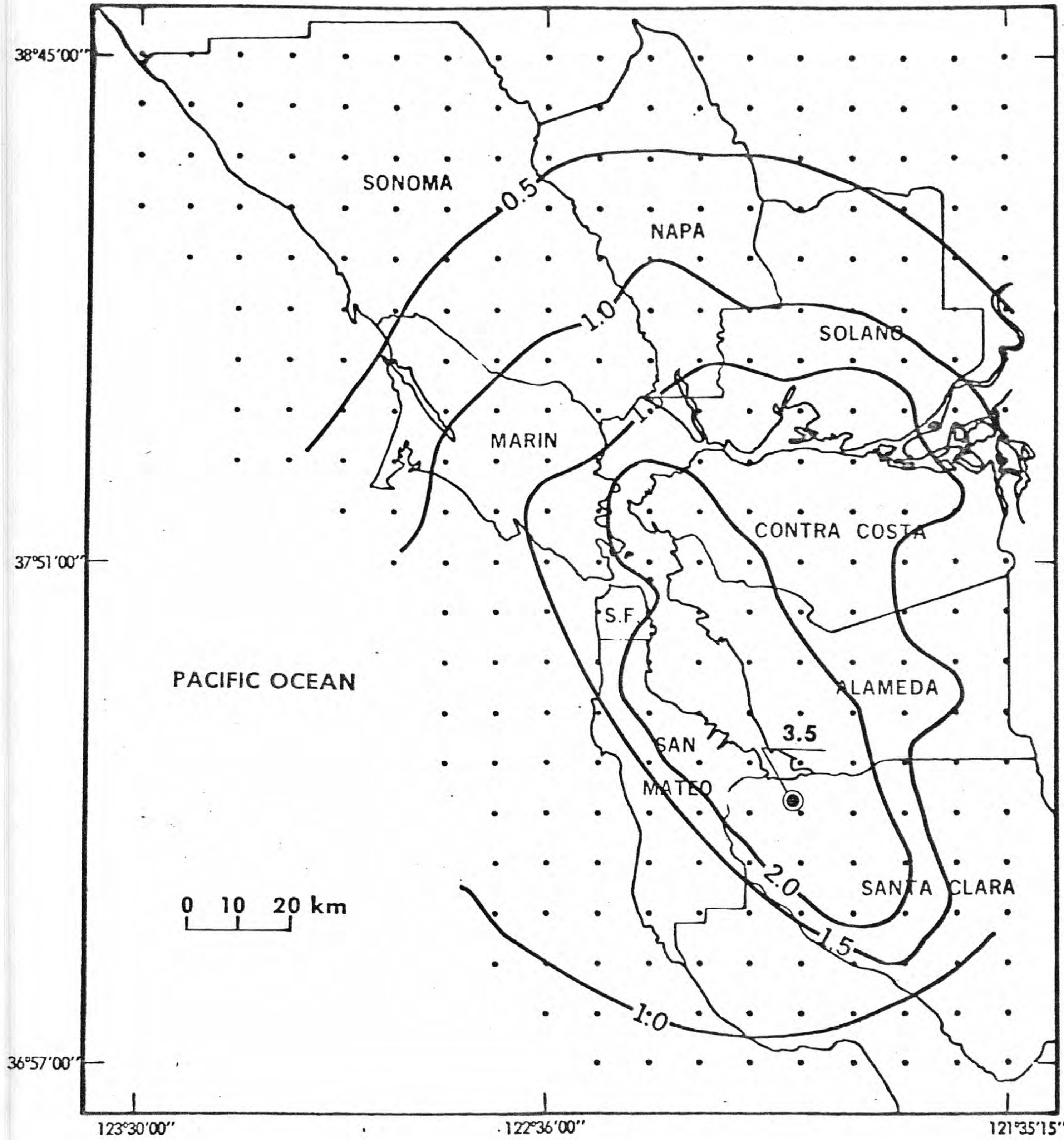

Figure A23.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LC for an earthquake with maximum intensity I_o=VII.

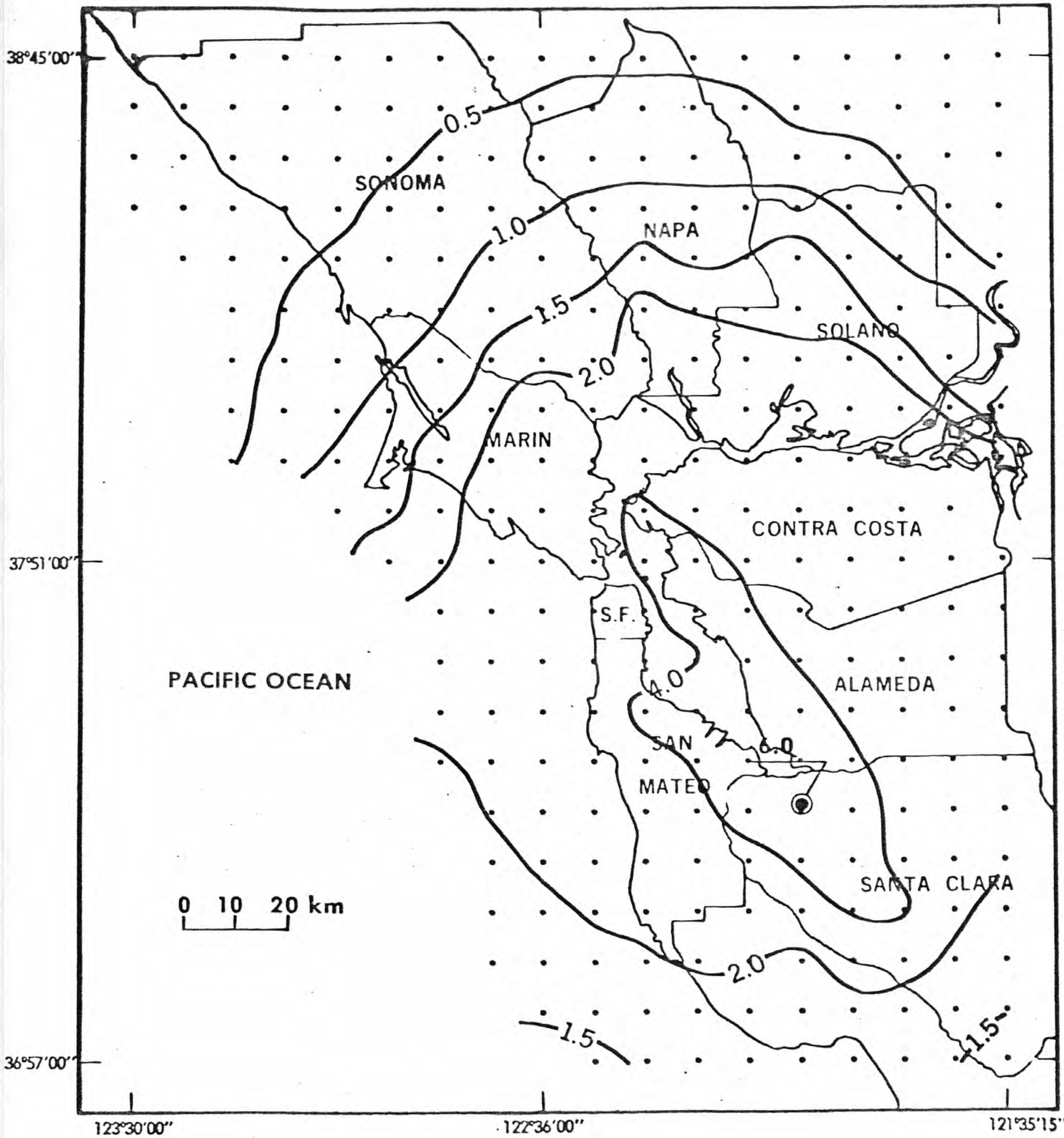

Figure A24.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LD for an earthquake with maximum intensity I_o=VII.

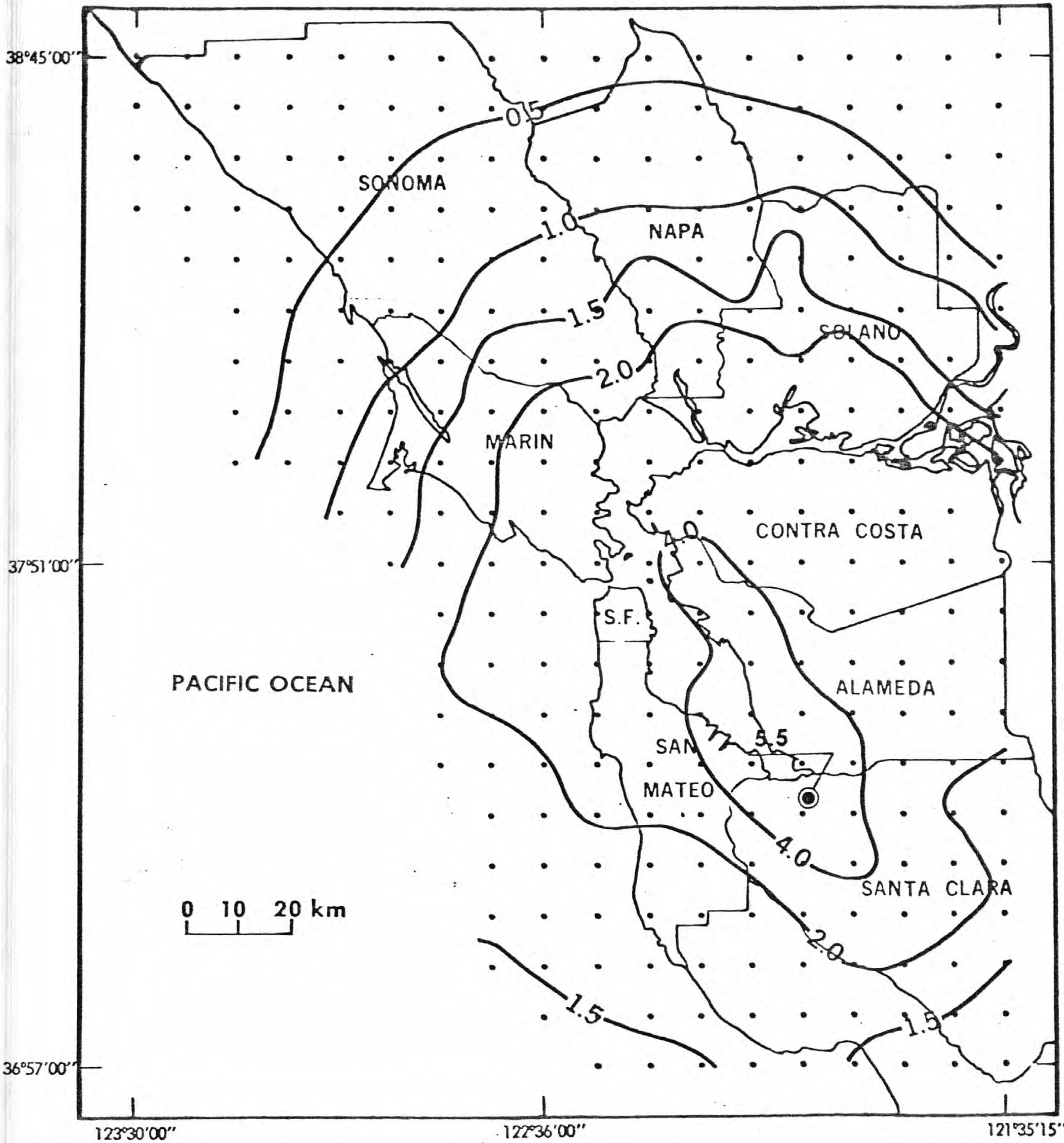

Figure A25.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LE for an earthquake with maximum intensity I_o=VII.

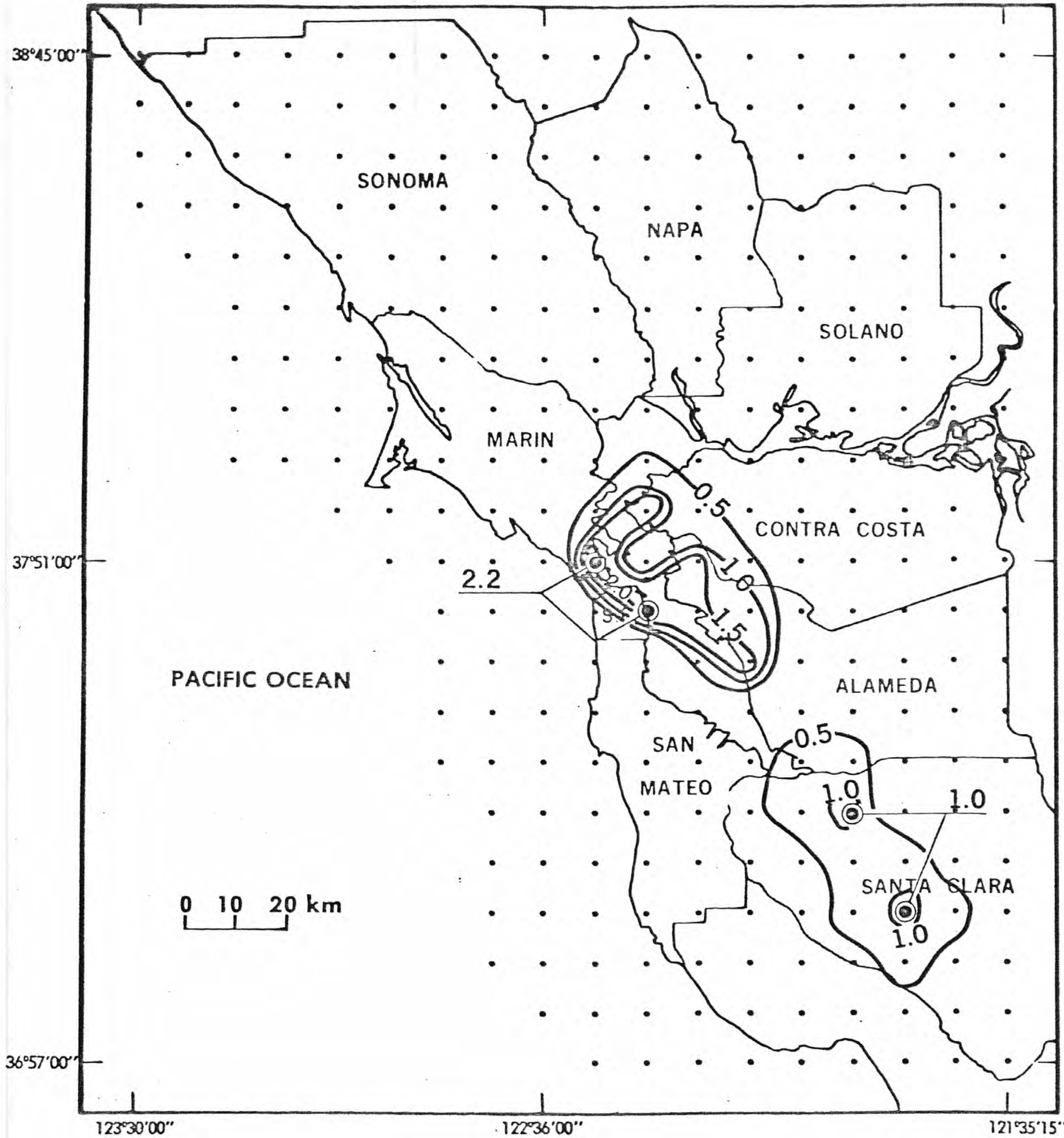

Figure A26.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HB for an earthquake with maximum intensity I_o=VII.

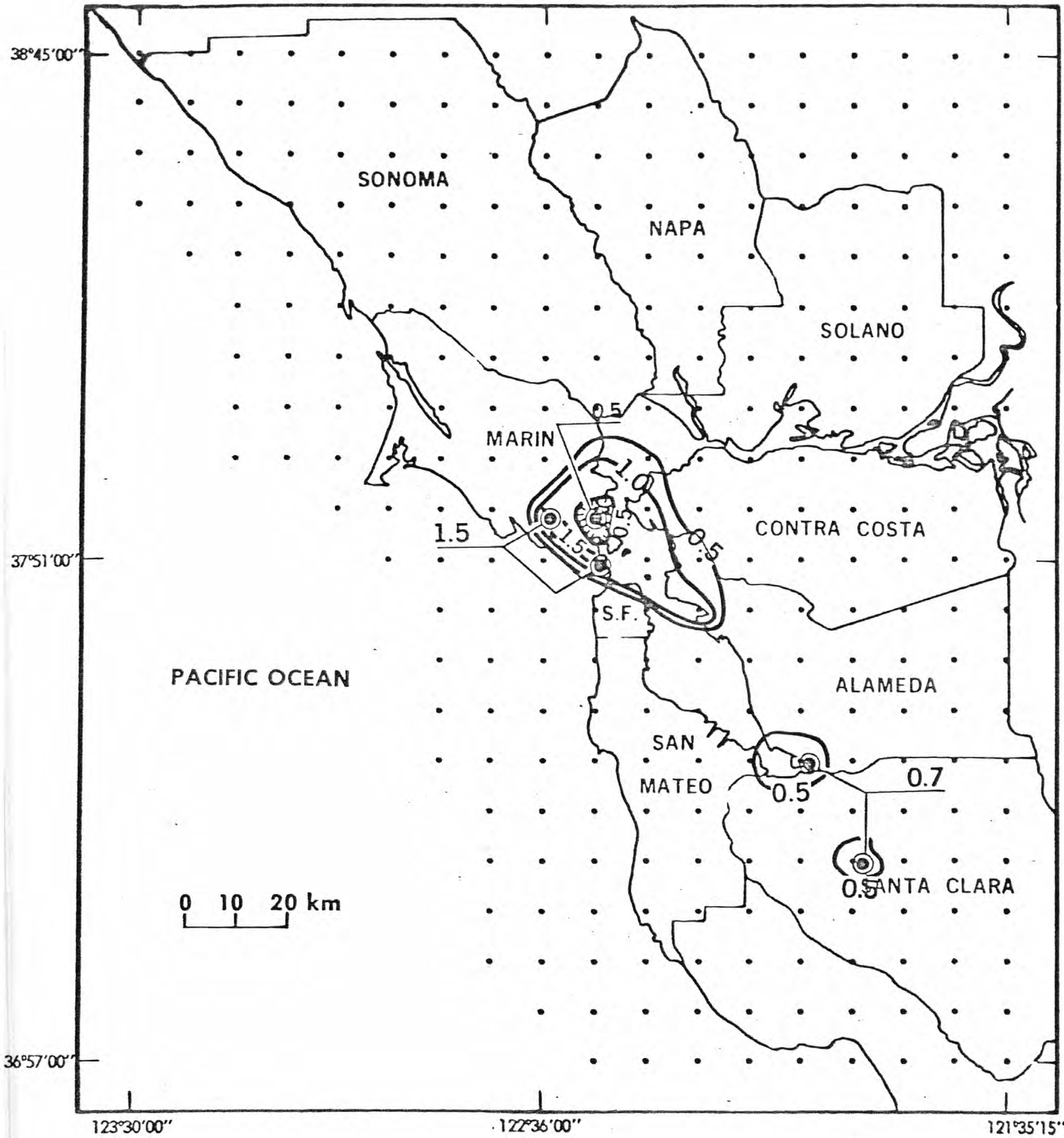

Figure A27.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HC for an earthquake with maximum intensity I_o=VII.

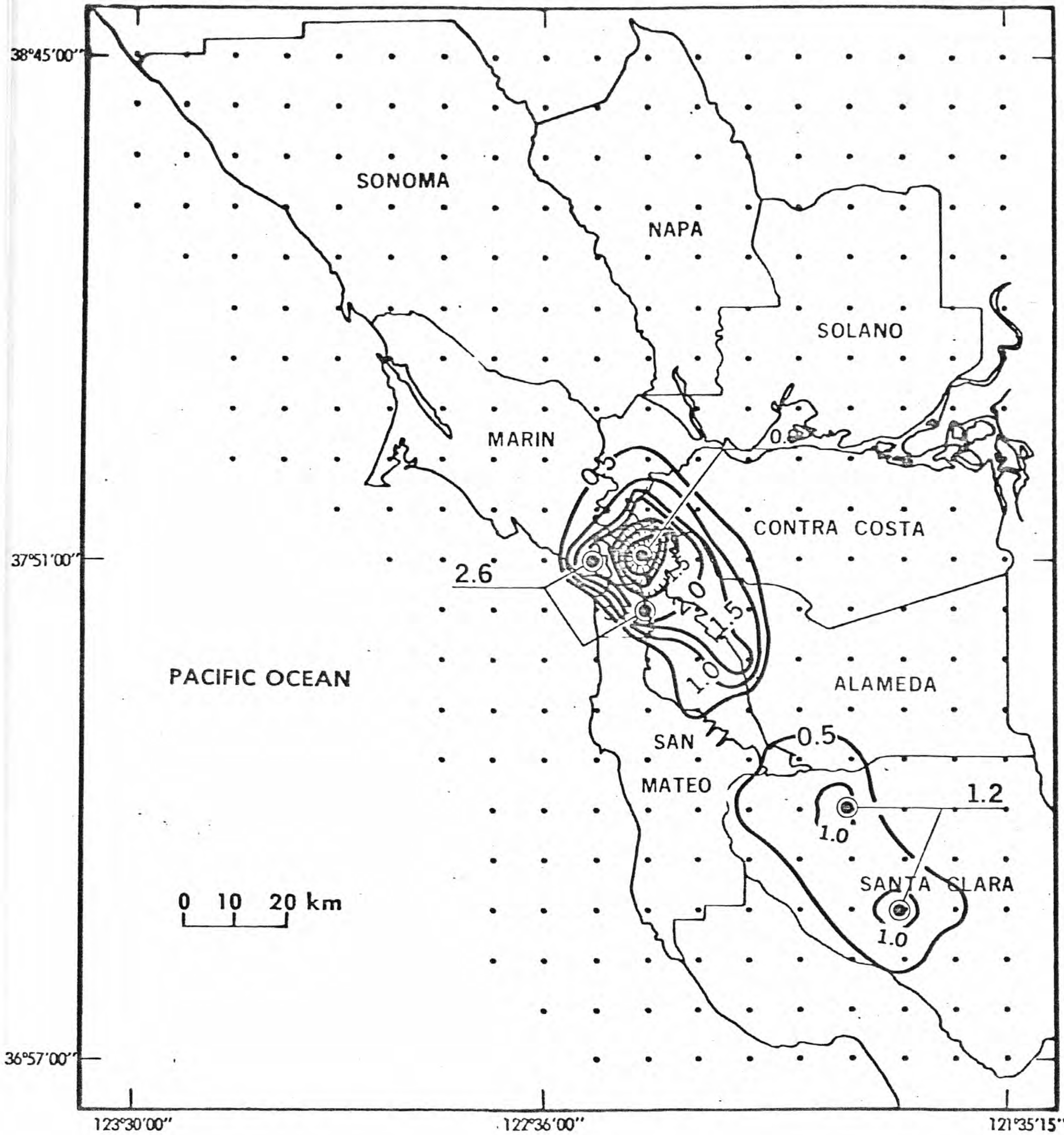

Figure A28.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HD for an earthquake with maximum intensity I_o=VII.

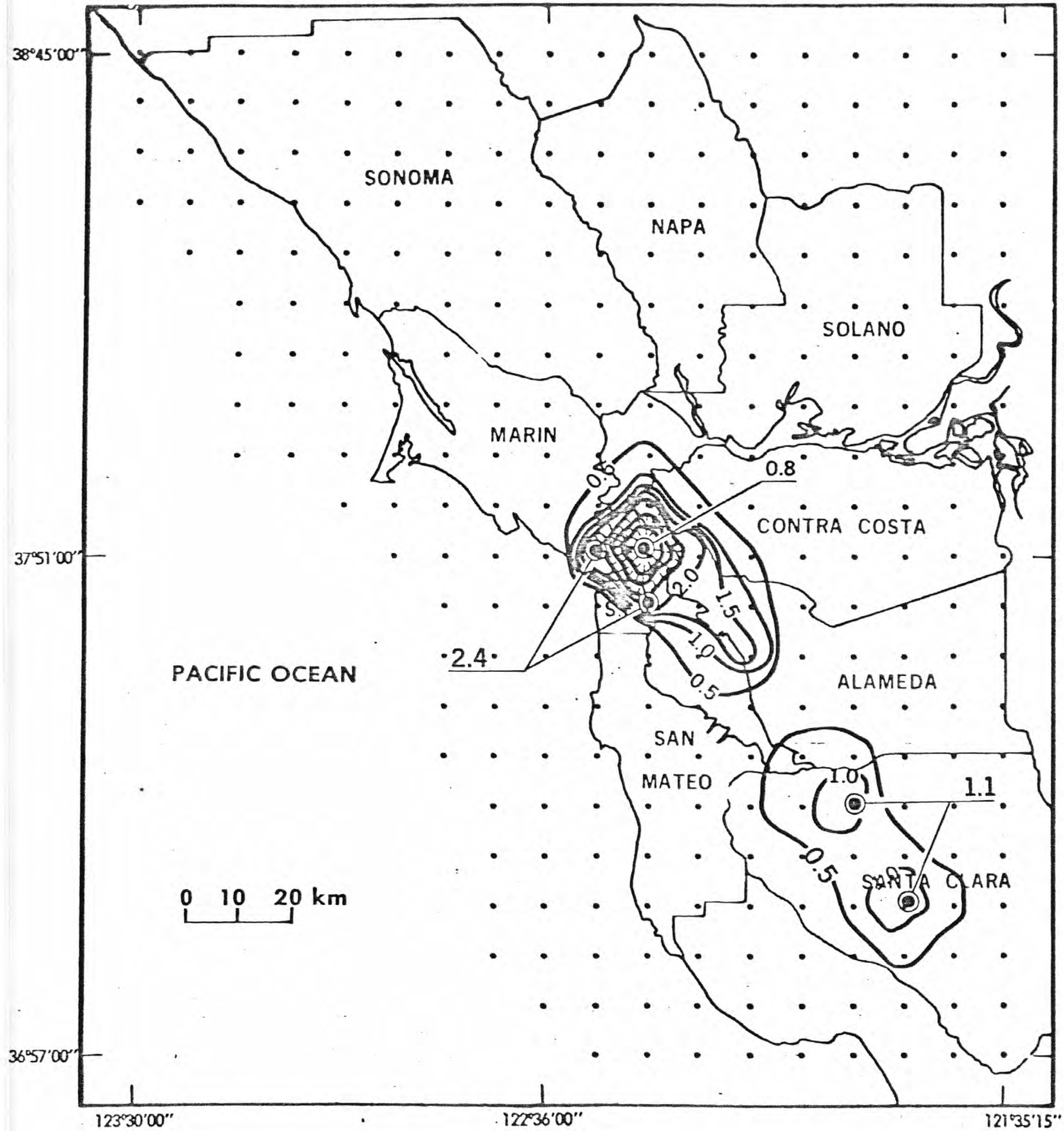

Figure A29.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HE for an earthquake with maximum intensity I_o=VII.

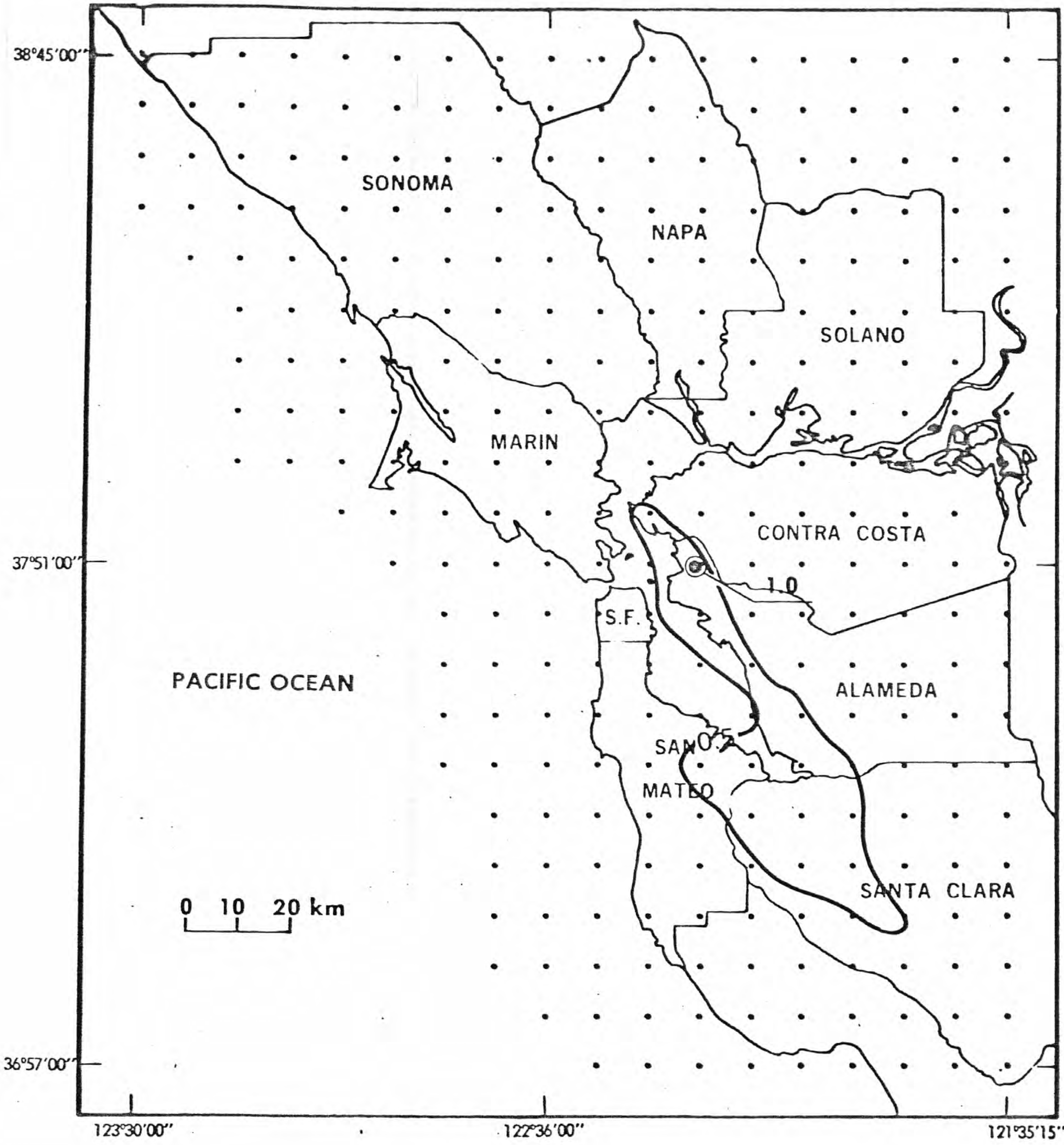

Figure A30.--Percent losses (contours) in the San Francisco Bay area for building subclass 5B for an earthquake with maximum intensity I_o=VII.

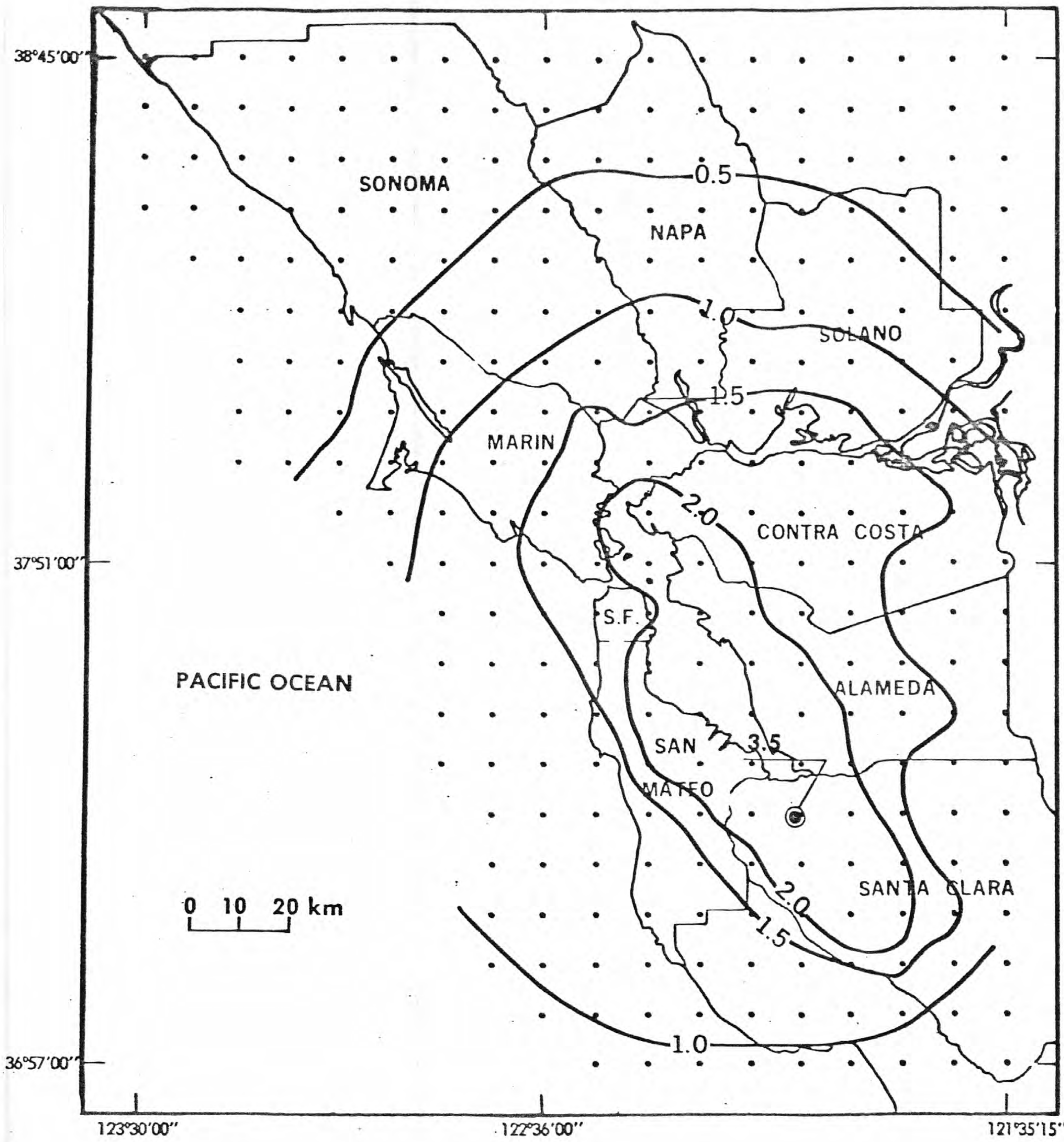

Figure A31.--Percent losses (contours) in the San Francisco Bay area for building subclass 5C for an earthquake with maximum intensity I_o=VII.

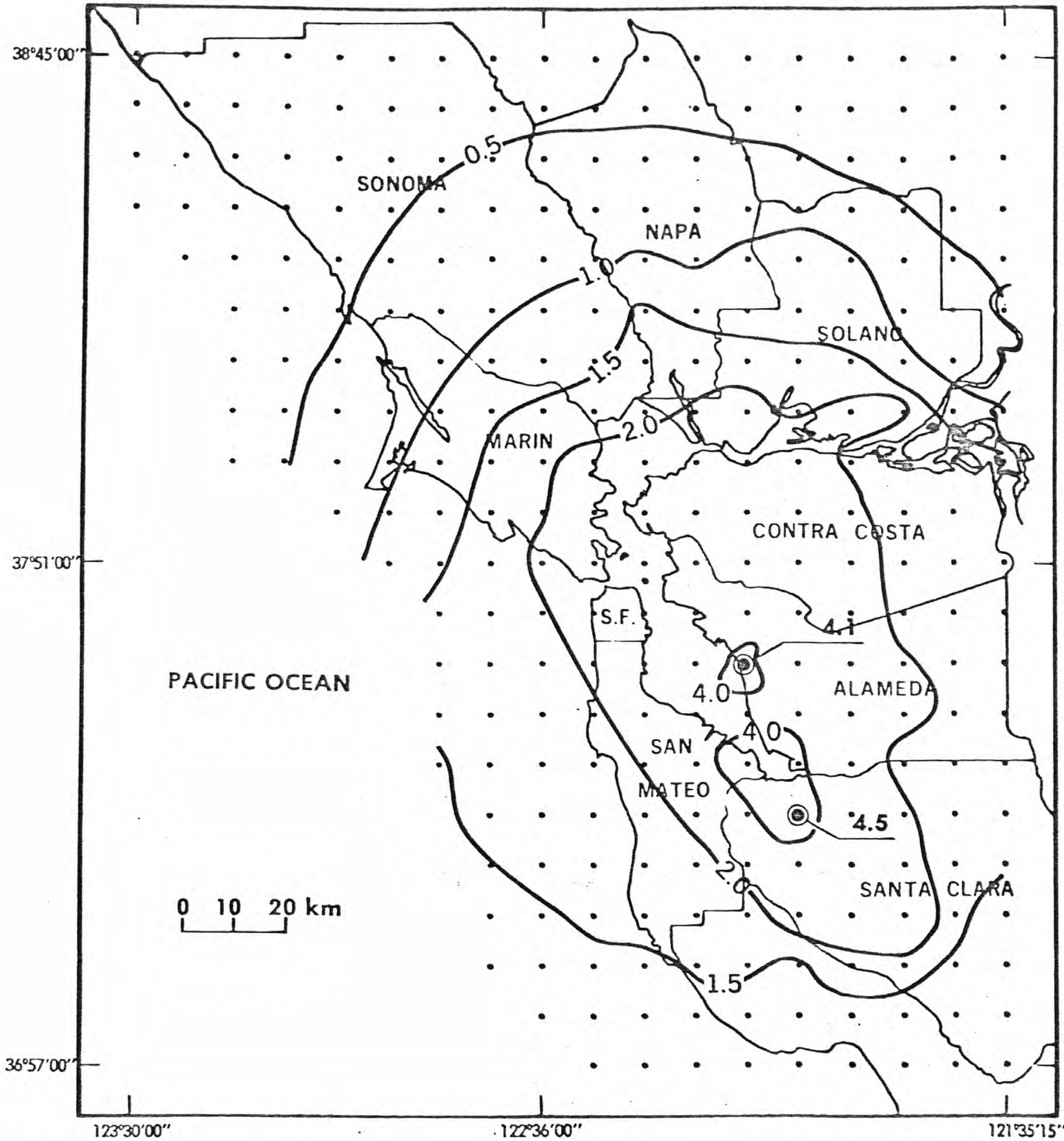

Figure A32.--Percent losses (contours) in the San Francisco Bay area for building subclass 5D for an earthquake with maximum intensity I_o=VII.

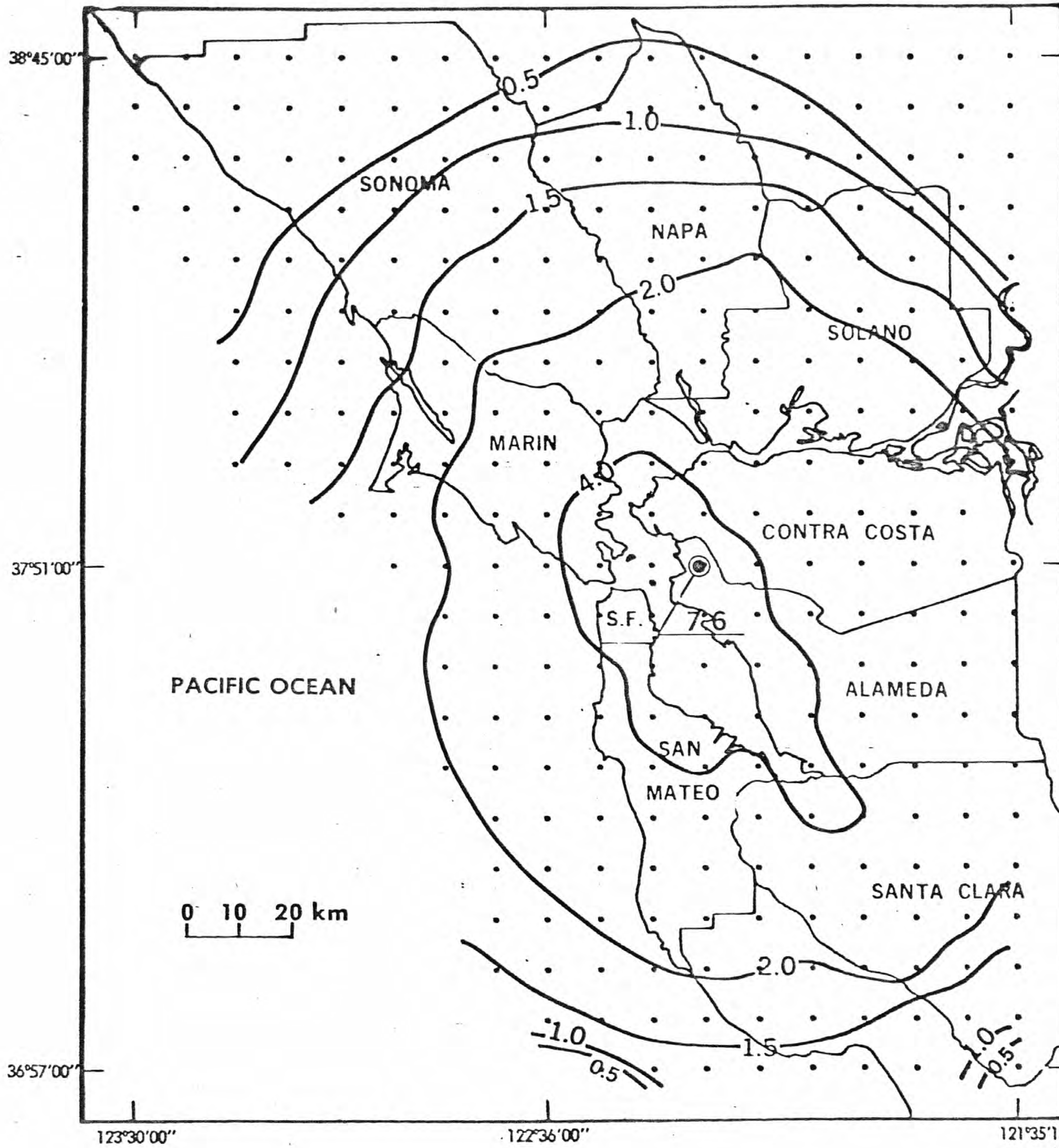

Figure A33.--Percent losses (contours) in the San Francisco Bay area for building subclass 5E for an earthquake with maximum intensity I_o=VII.

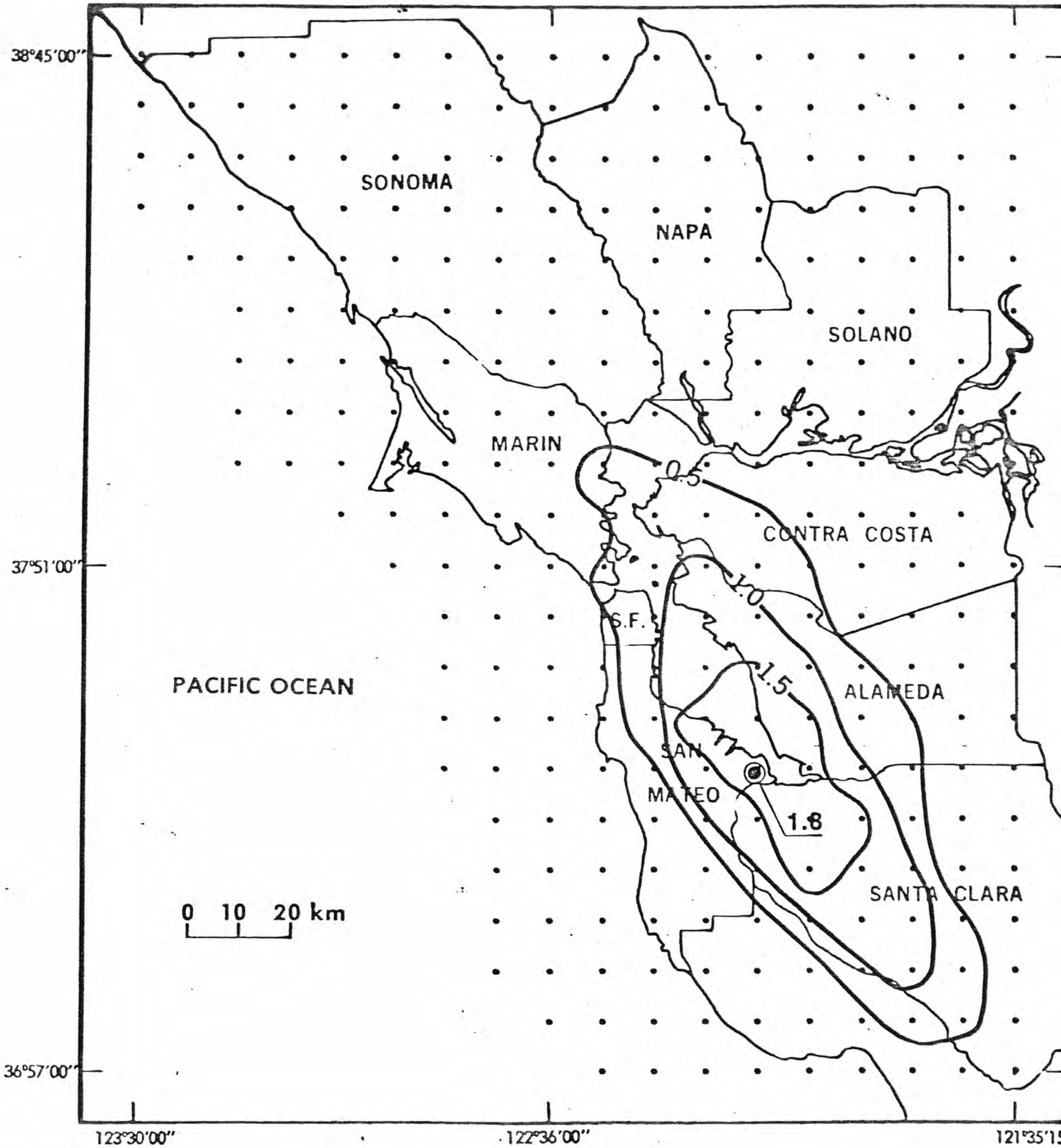

Figure A34.--Percent losses (contours) in the San Francisco Bay area for building subclass 2A for an earthquake with maximum intensity I_o=VIII.

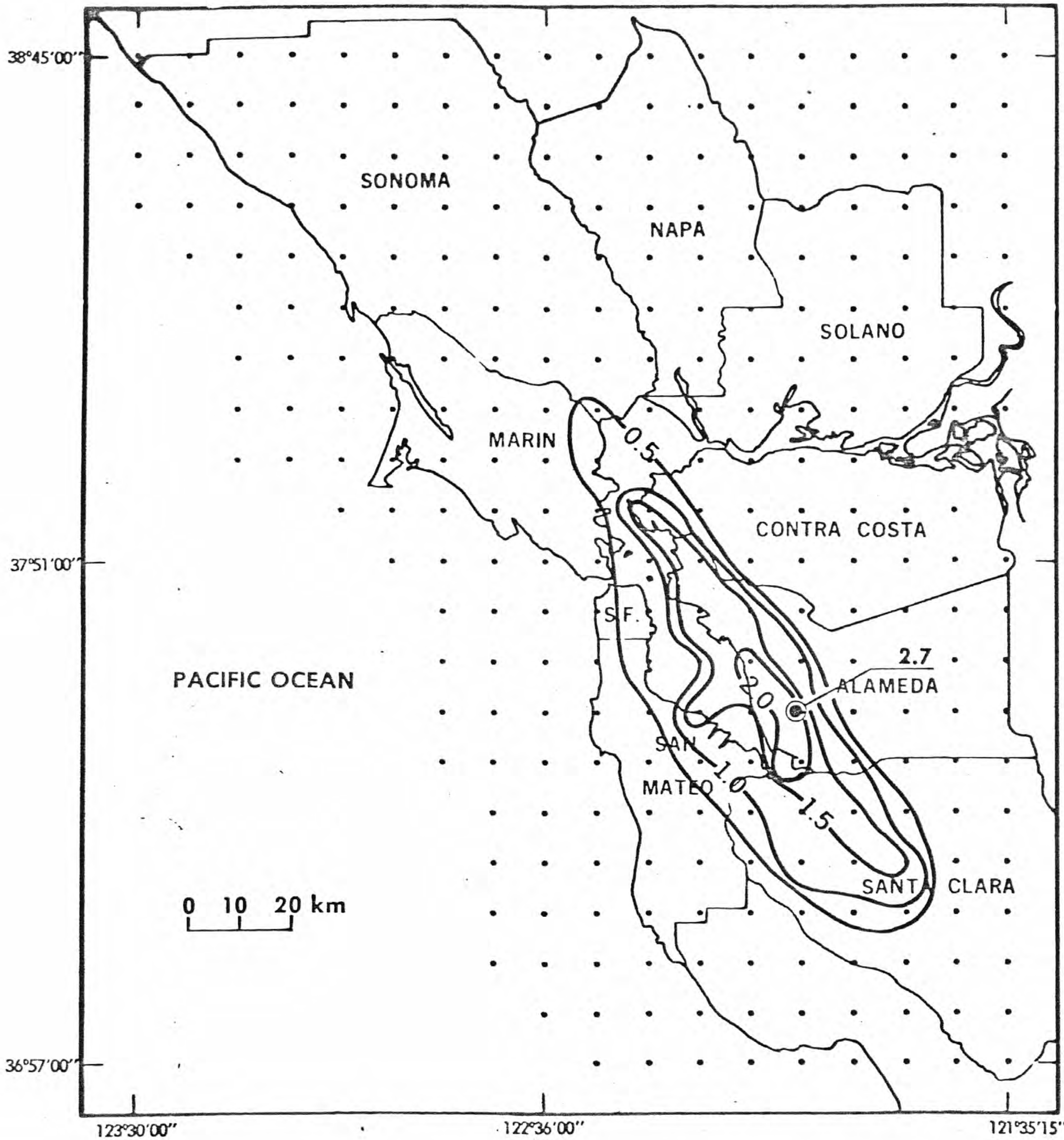

Figure A35.--Percent losses (contours) in the San Francisco Bay area for building subclass 2B for an earthquake with maximum intensity I_o=VIII.

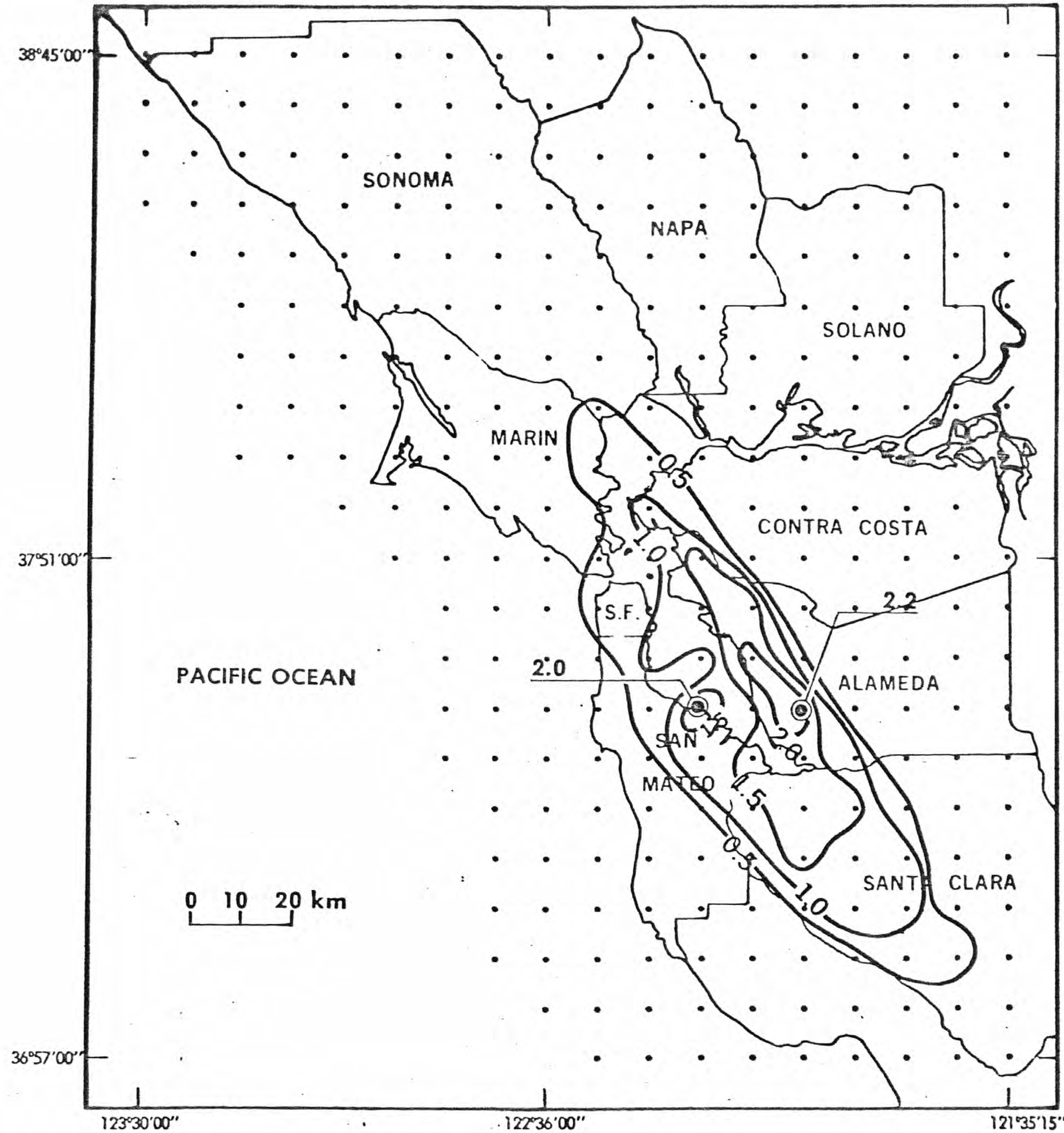

Figure A36.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LA for an earthquake with maximum intensity I_o=VIII.

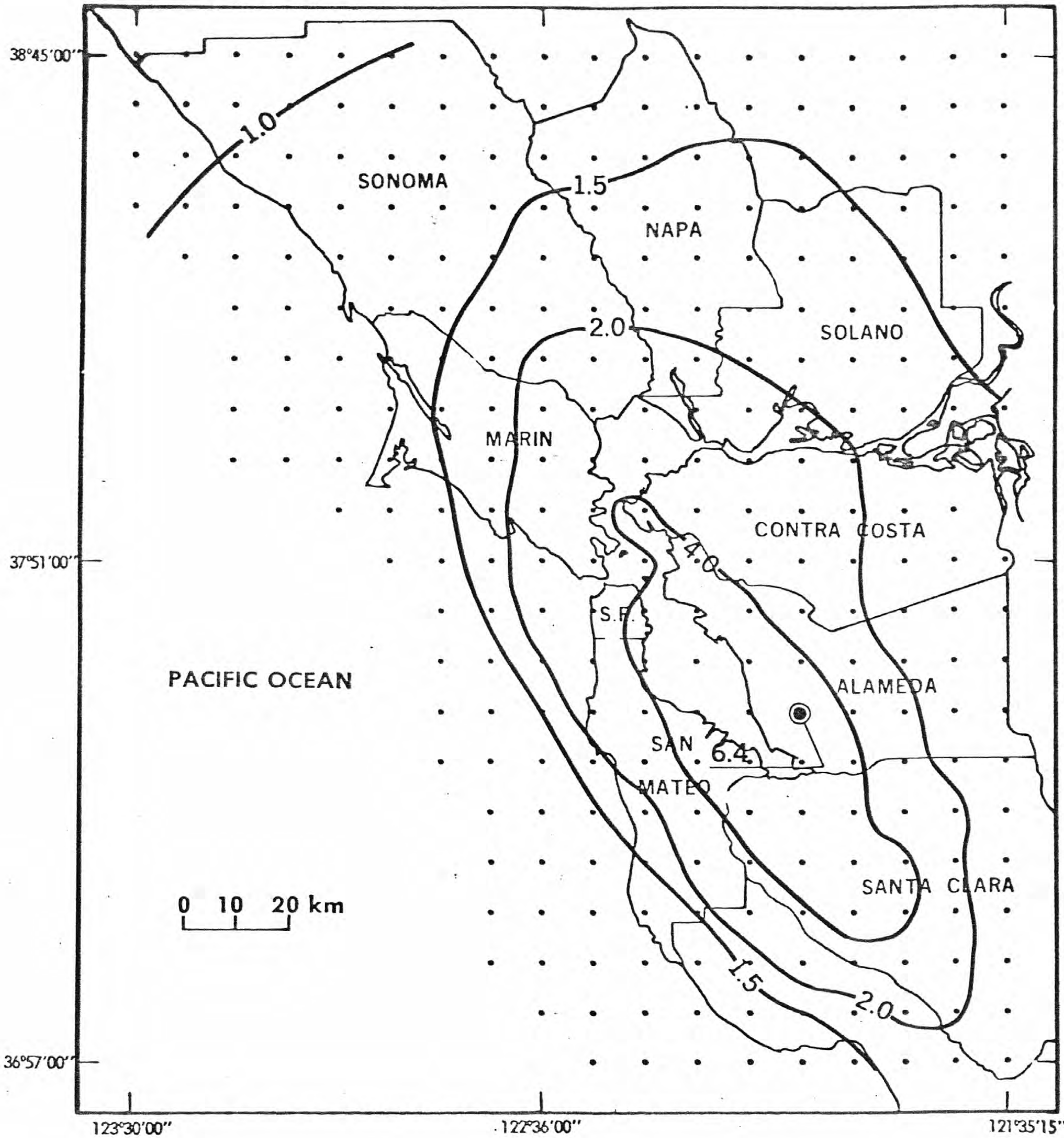

Figure A37.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LB for an earthquake with maximum intensity I_o=VIII.

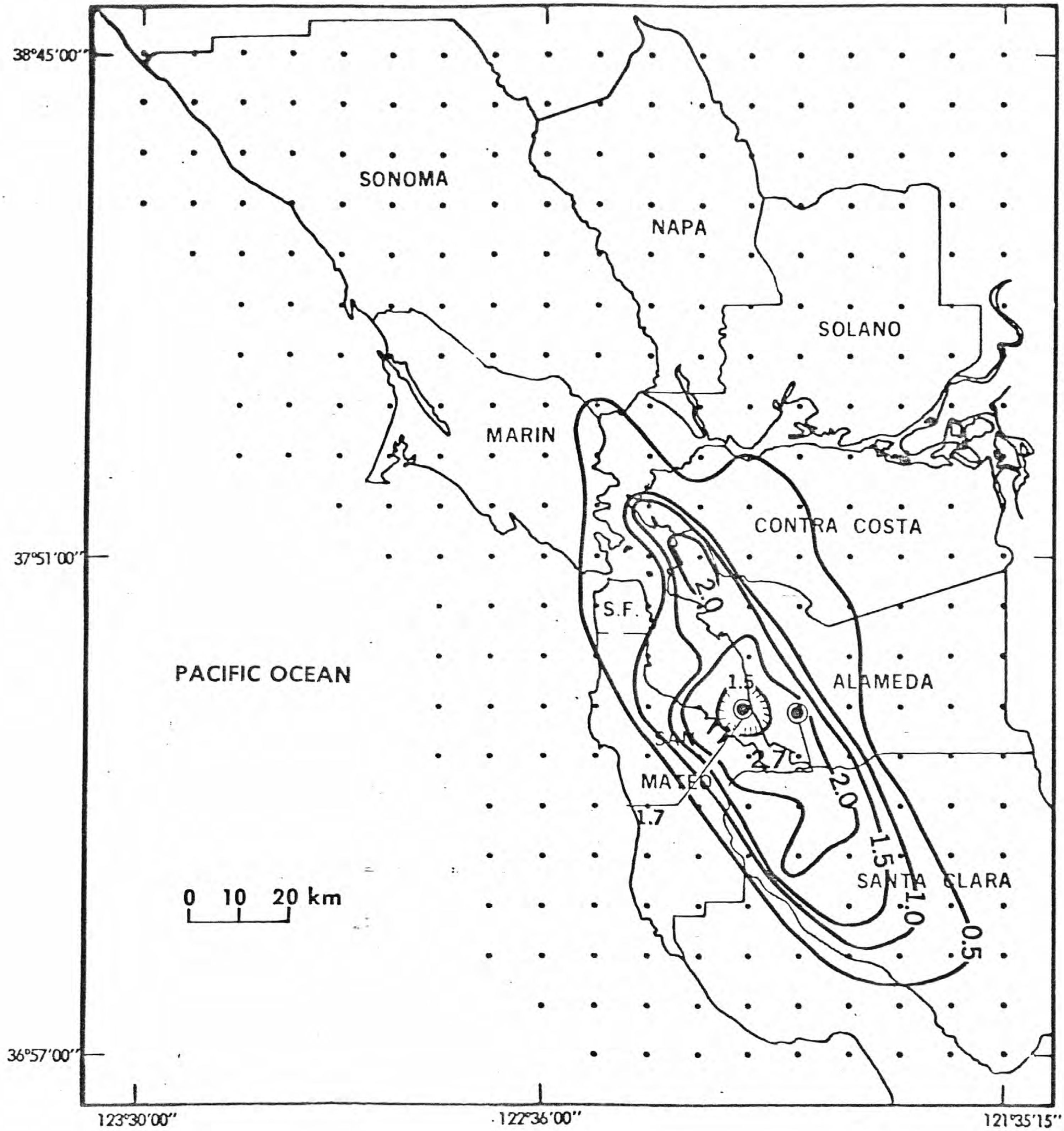

Figure A38.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LC for an earthquake with maximum intensity I_o=VIII.

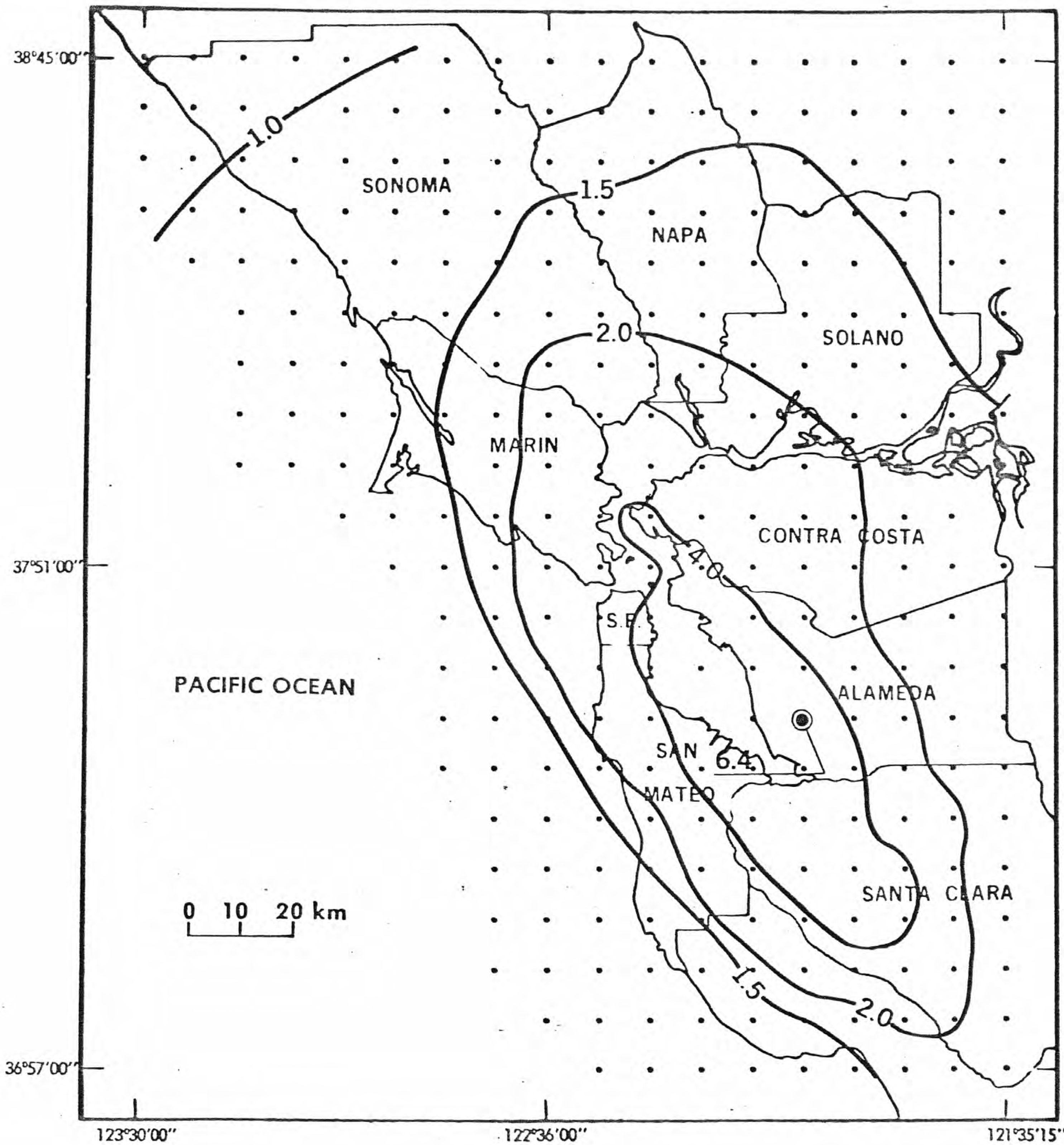

Figure A39.--Percent losses (contours) in the San Francisco Bay area for building subclass 3LD for an earthquake with maximum intensity I_o=VIII.

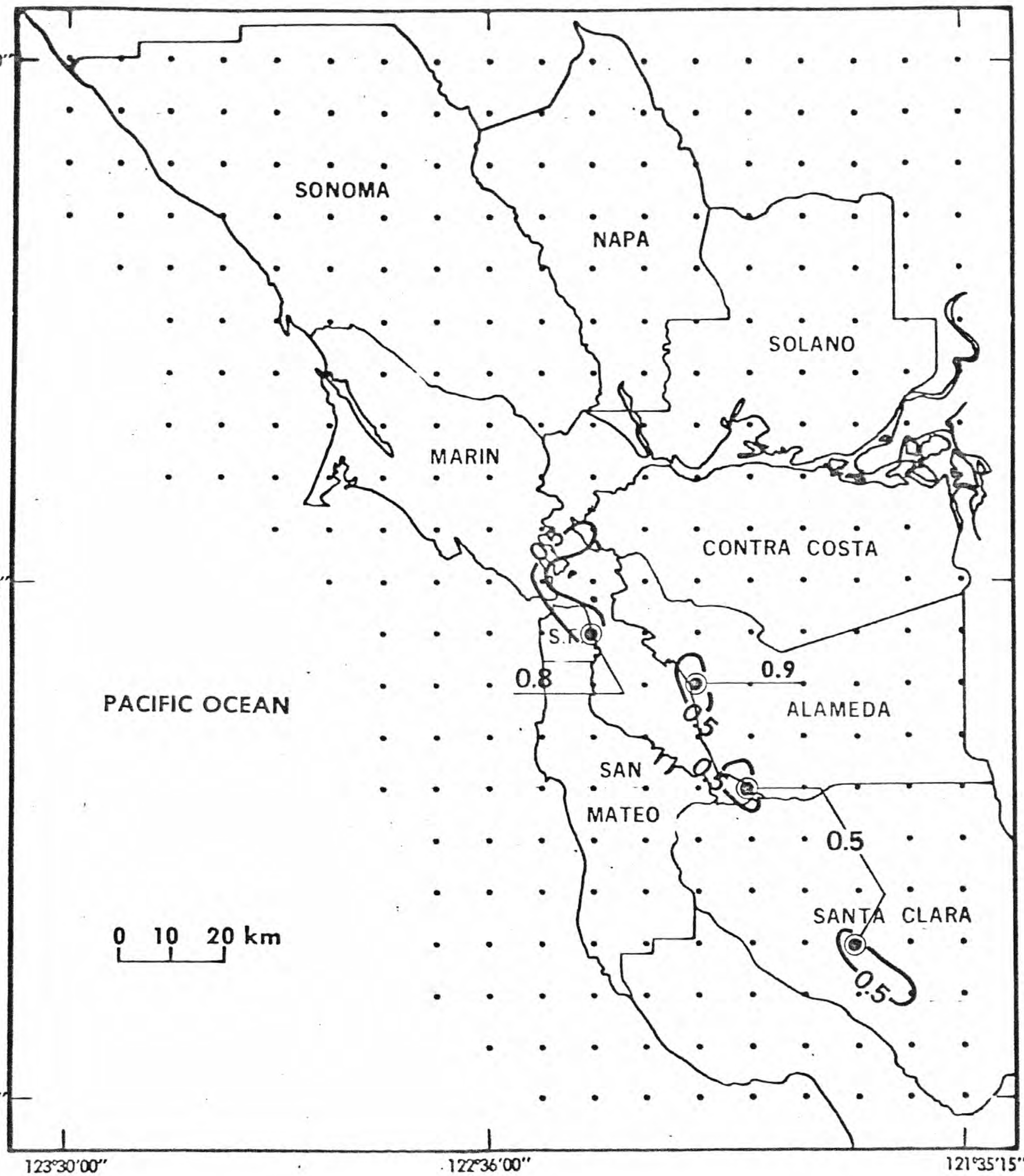

Figure A40.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HA for an earthquake with maximum intensity I_o=VIII.

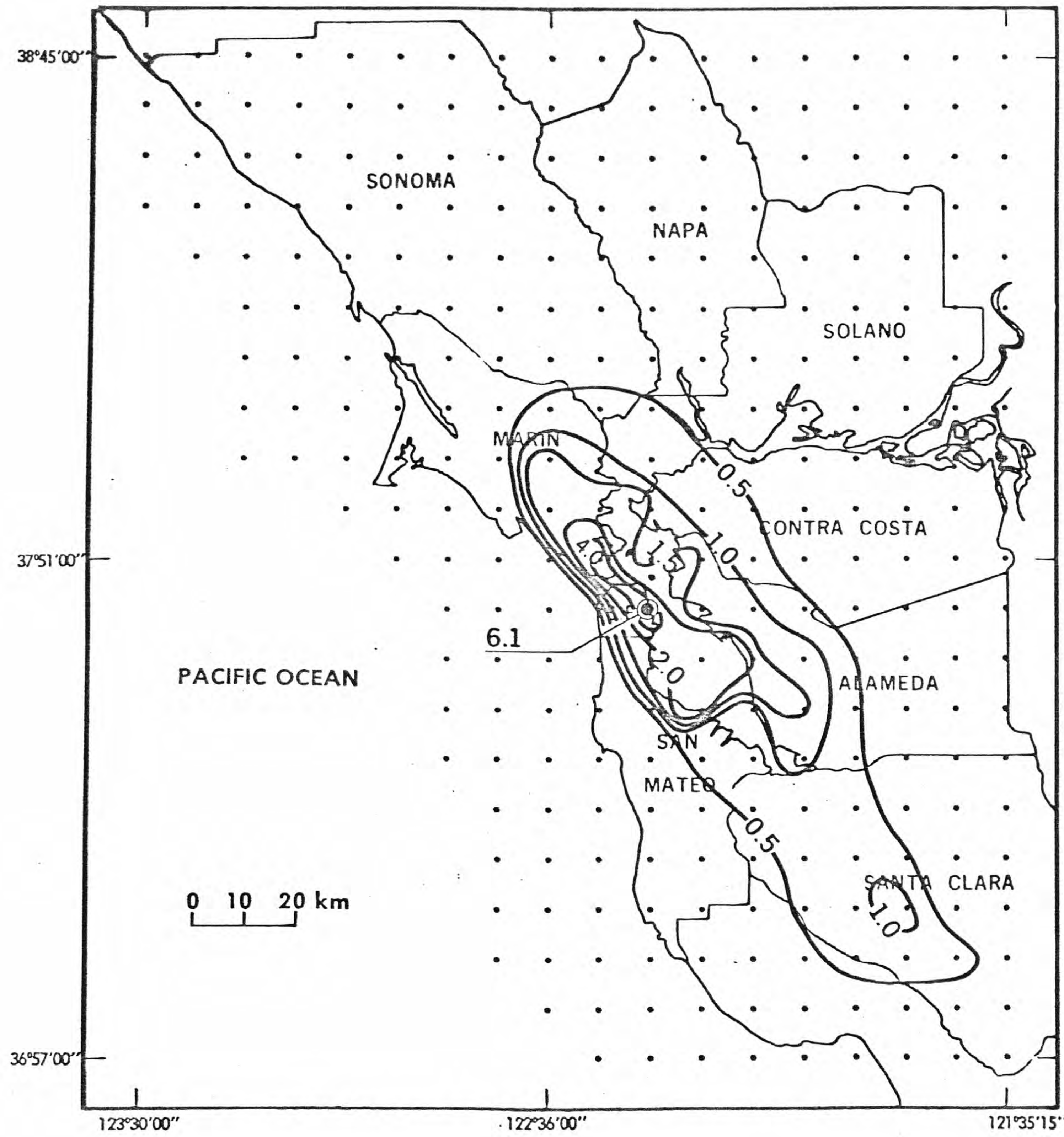

Figure A41.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HB for an earthquake with maximum intensity I_o=VIII.

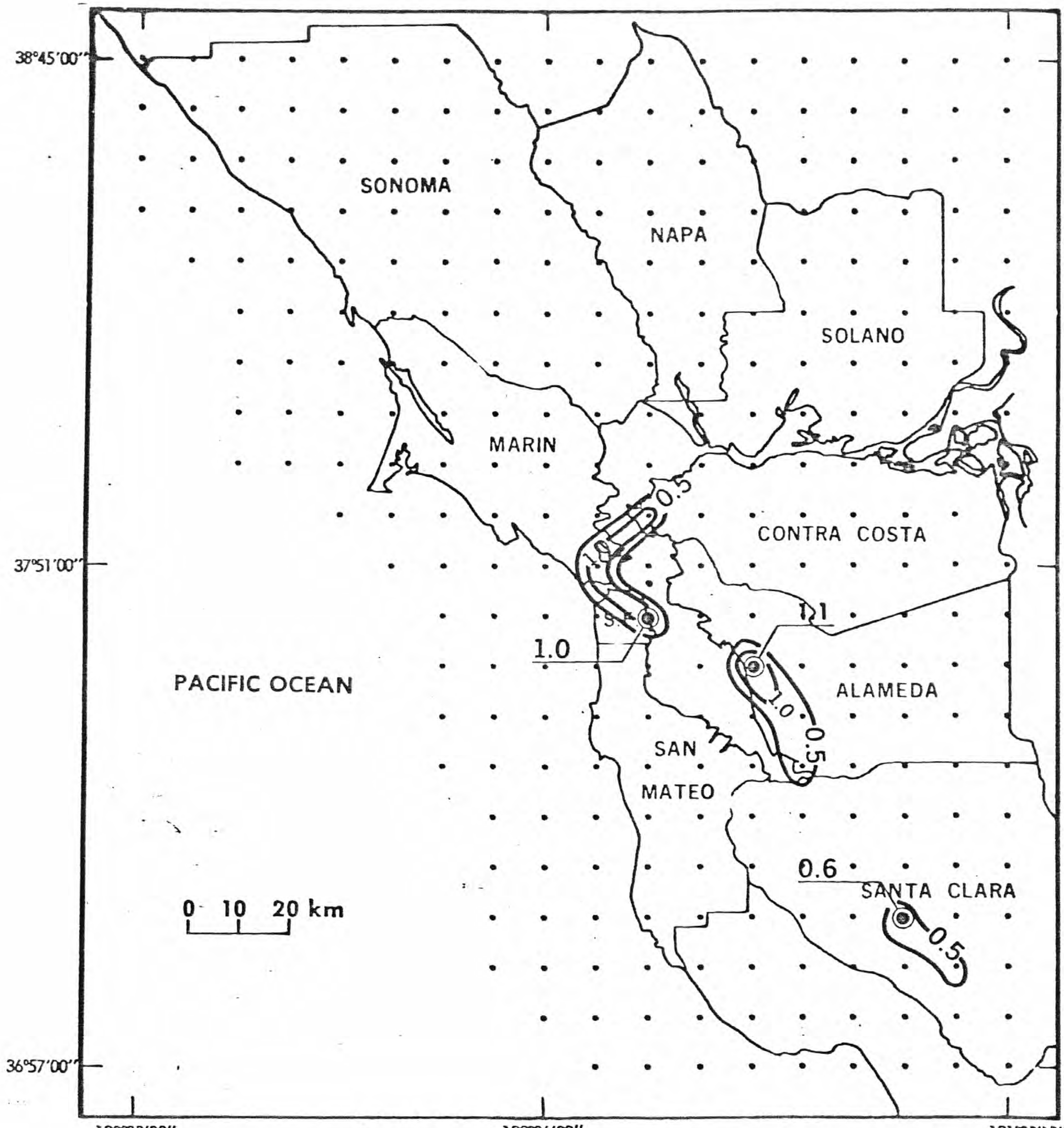

Figure A42.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HC for an earthquake with maximum intensity I_o=VIII.

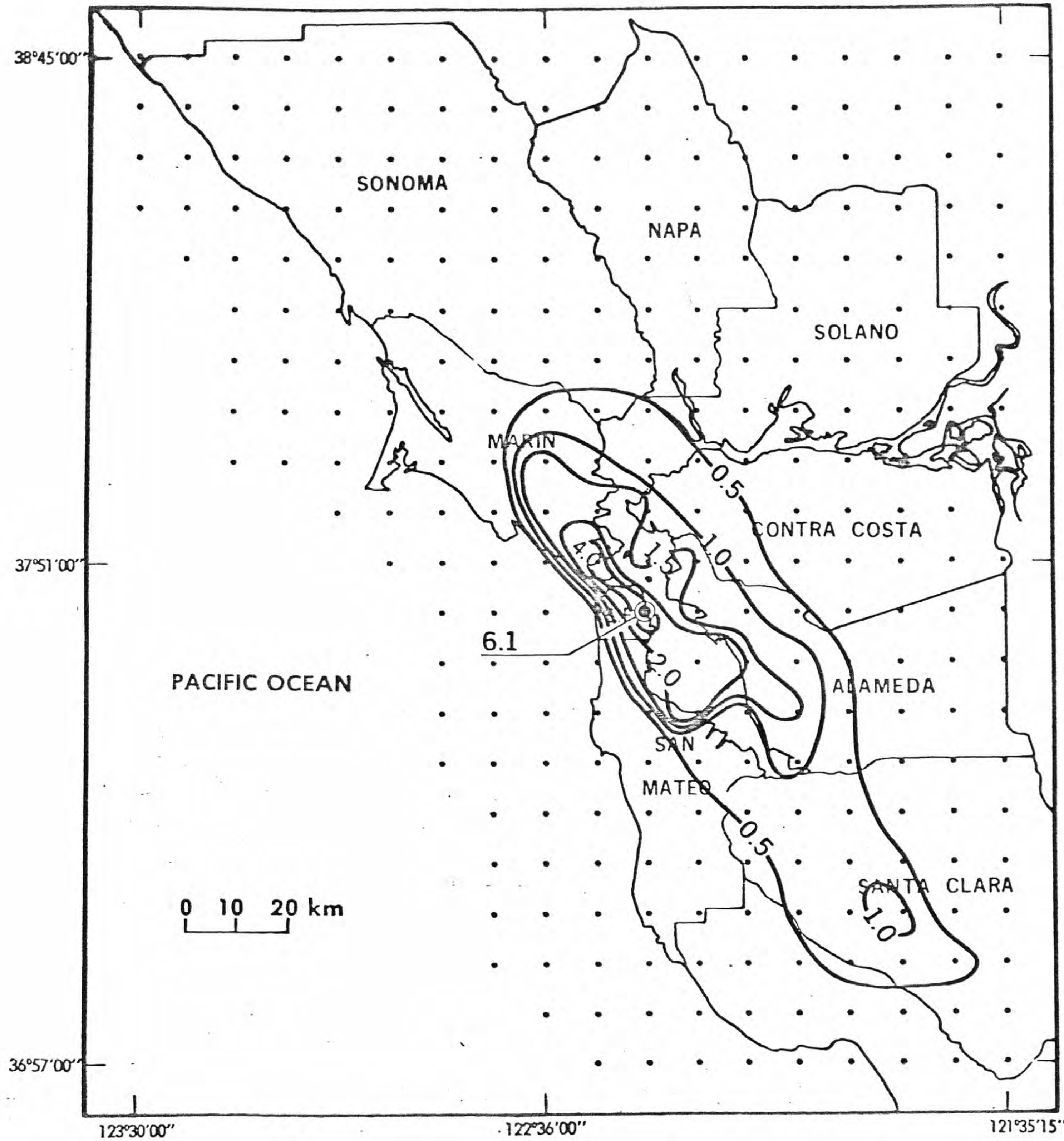

Figure A43.--Percent losses (contours) in the San Francisco Bay area for building subclass 3HD for an earthquake with maximum intensity I_o=VIII.

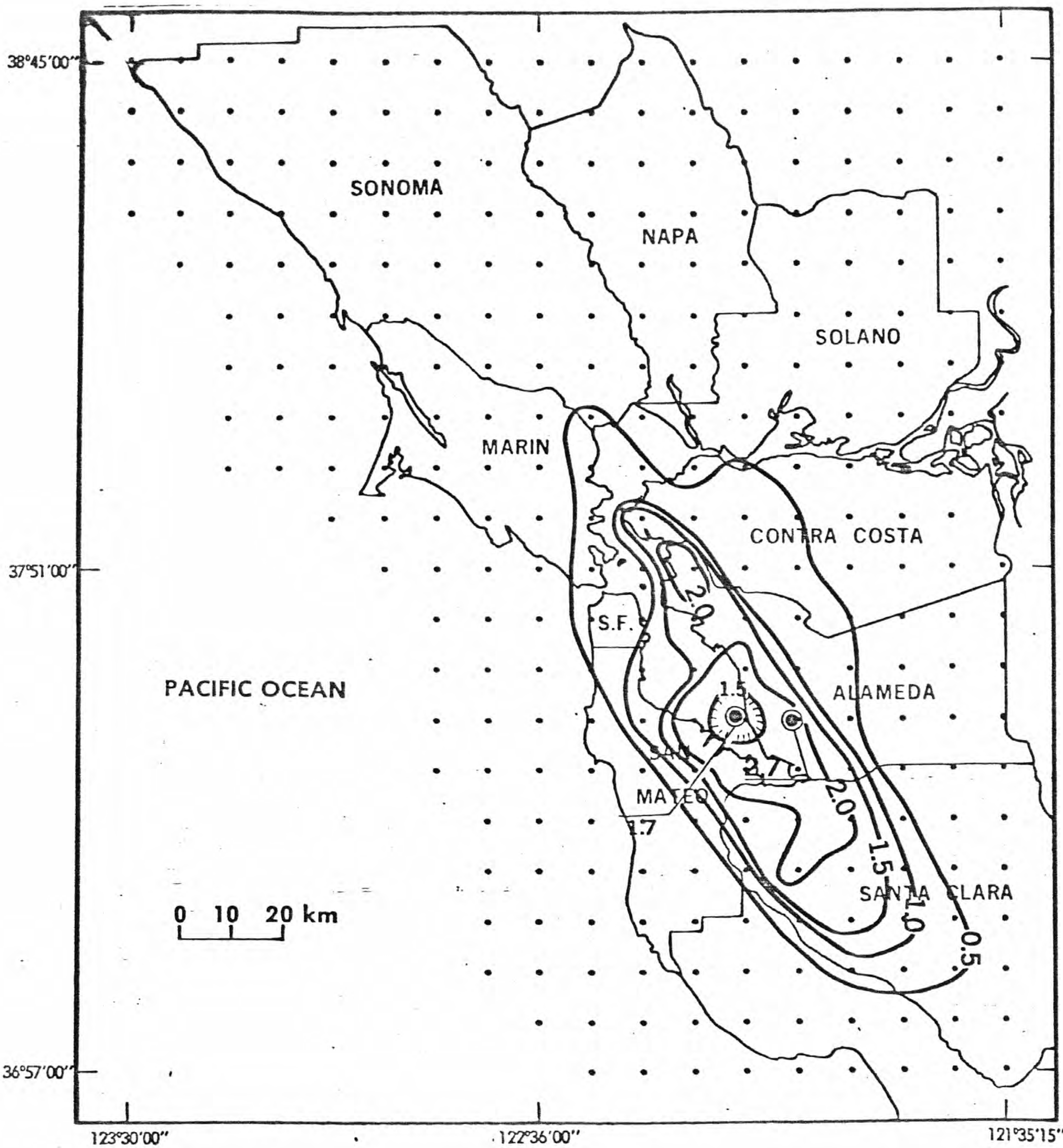

Figure A44.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LA for an earthquake with maximum intensity I_o=VIII.

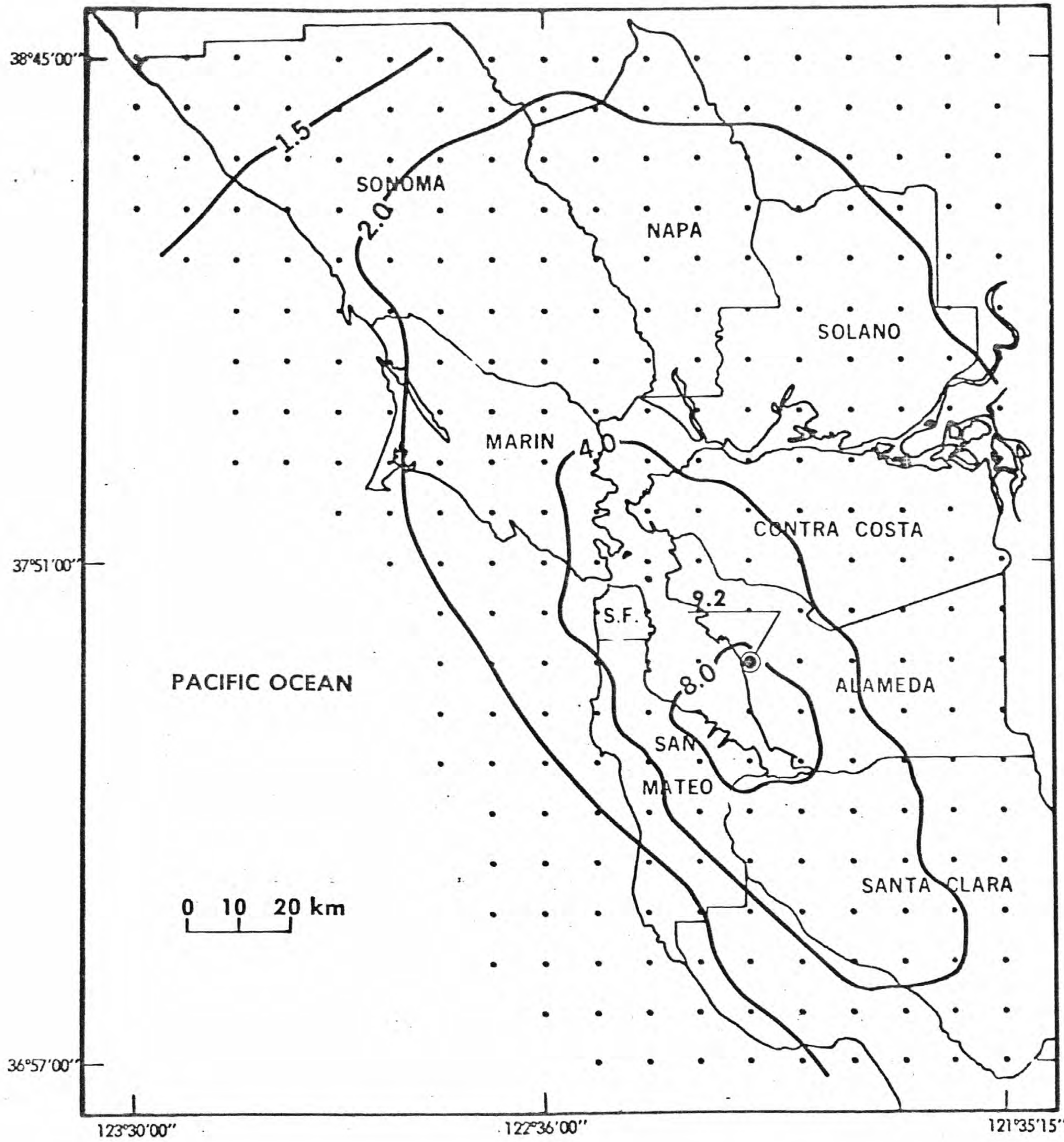

Figure A45.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LB for an earthquake with maximum intensity I_o=VIII.

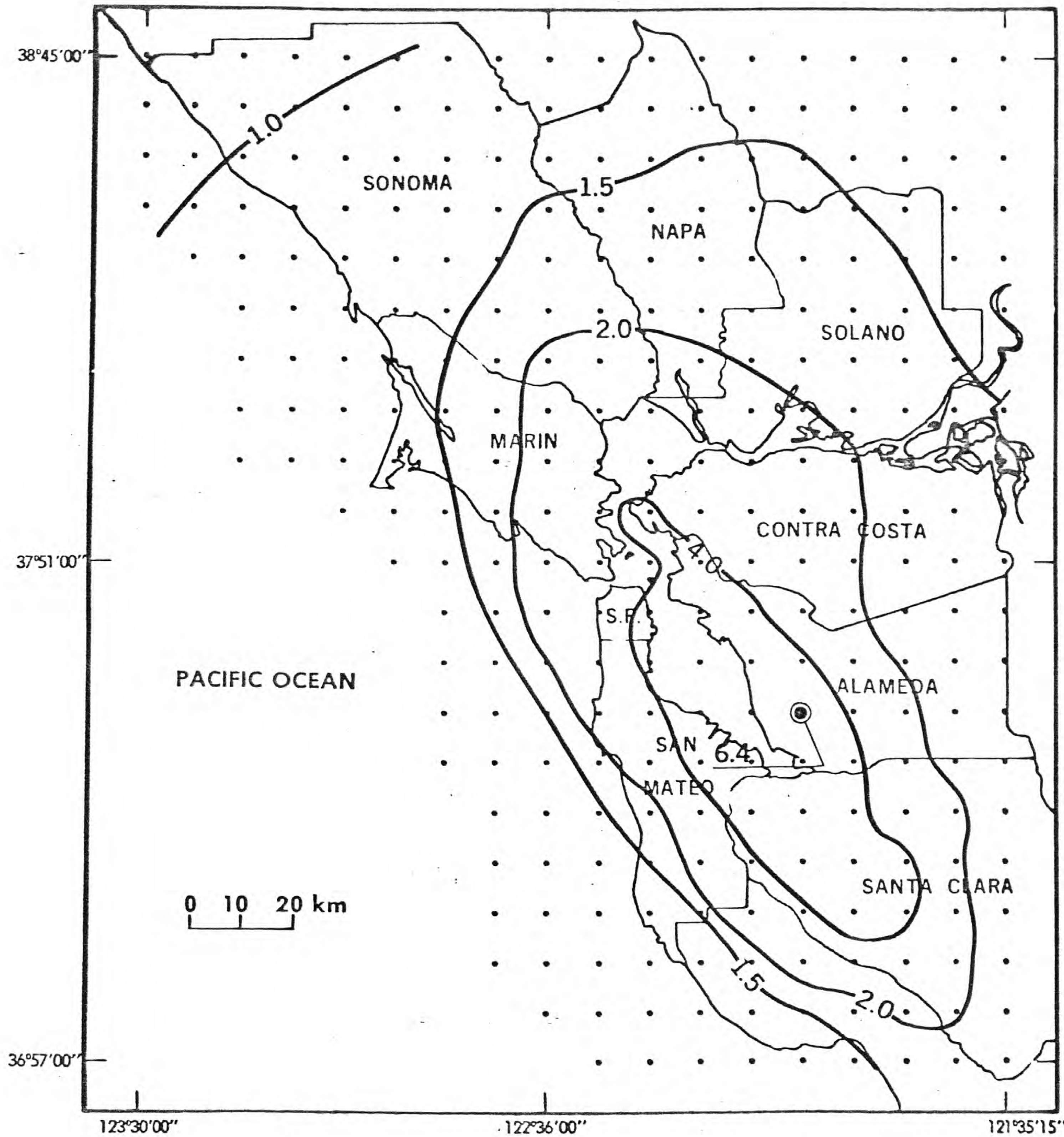

Figure A46.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LC for an earthquake with maximum intensity I_o=VIII.

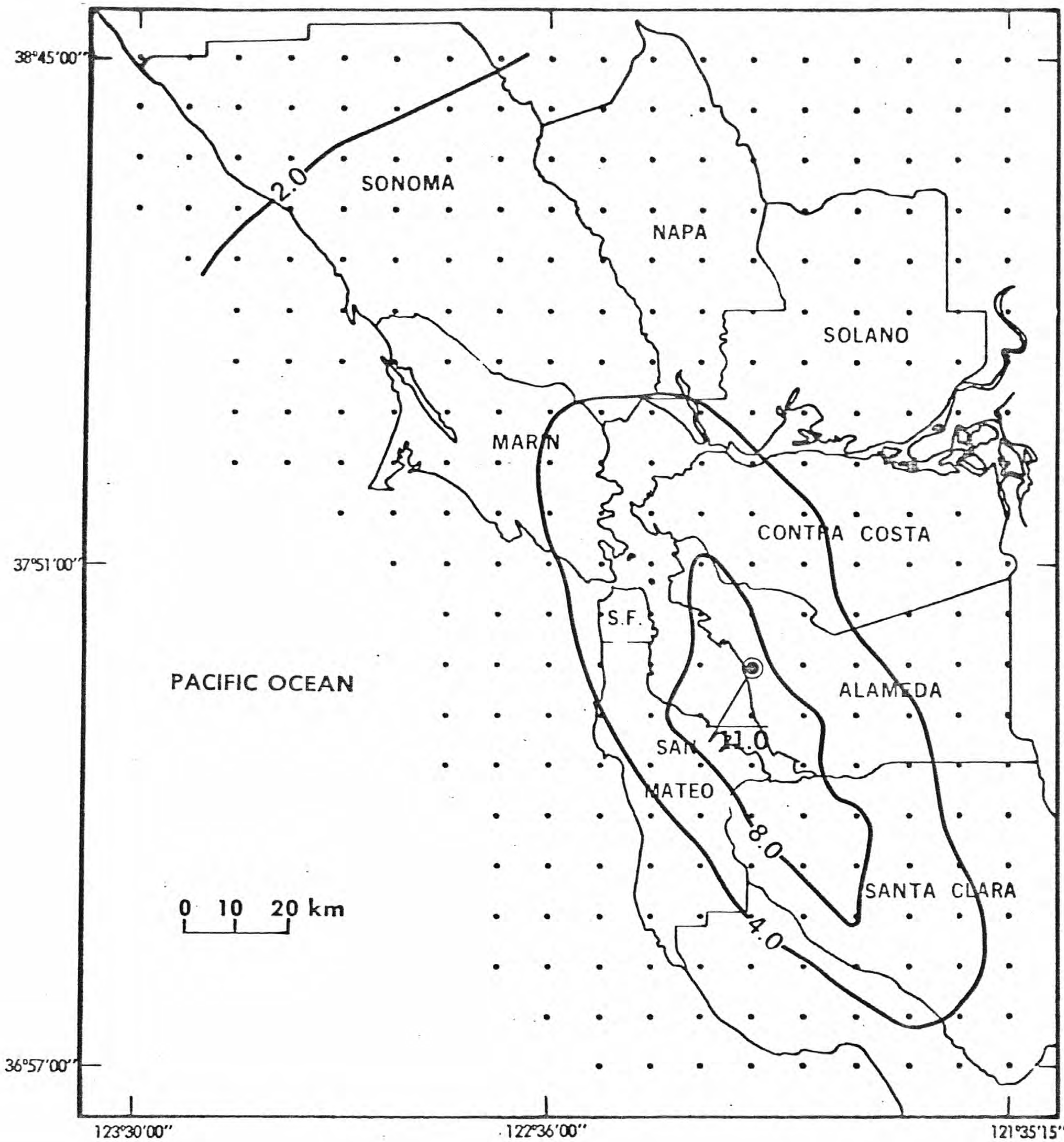

Figure A47.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LD for an earthquake with maximum intensity I_o=VIII.

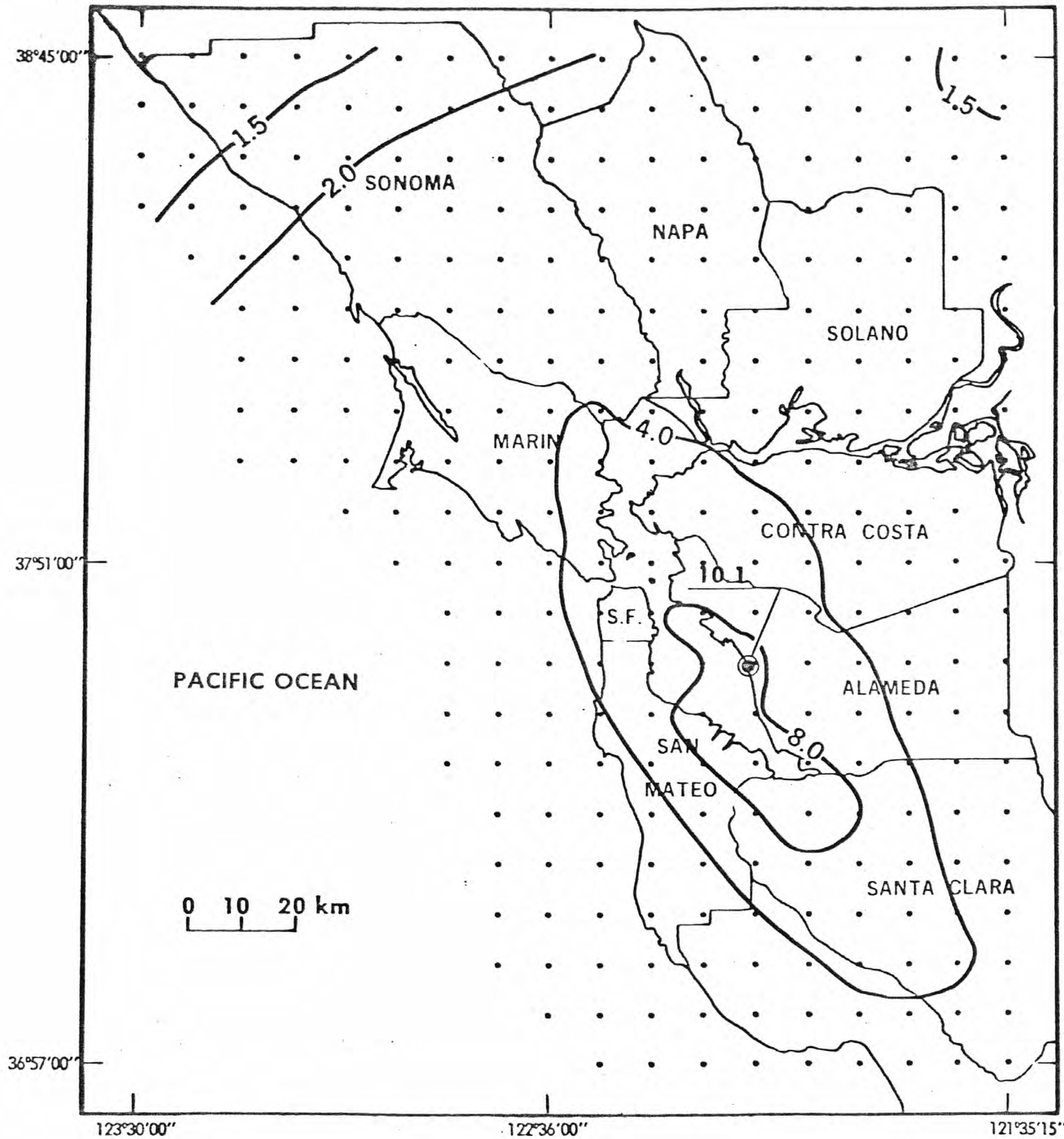

Figure A48.--Percent losses (contours) in the San Francisco Bay area for building subclass 4LE for an earthquake with maximum intensity I_o=VIII.

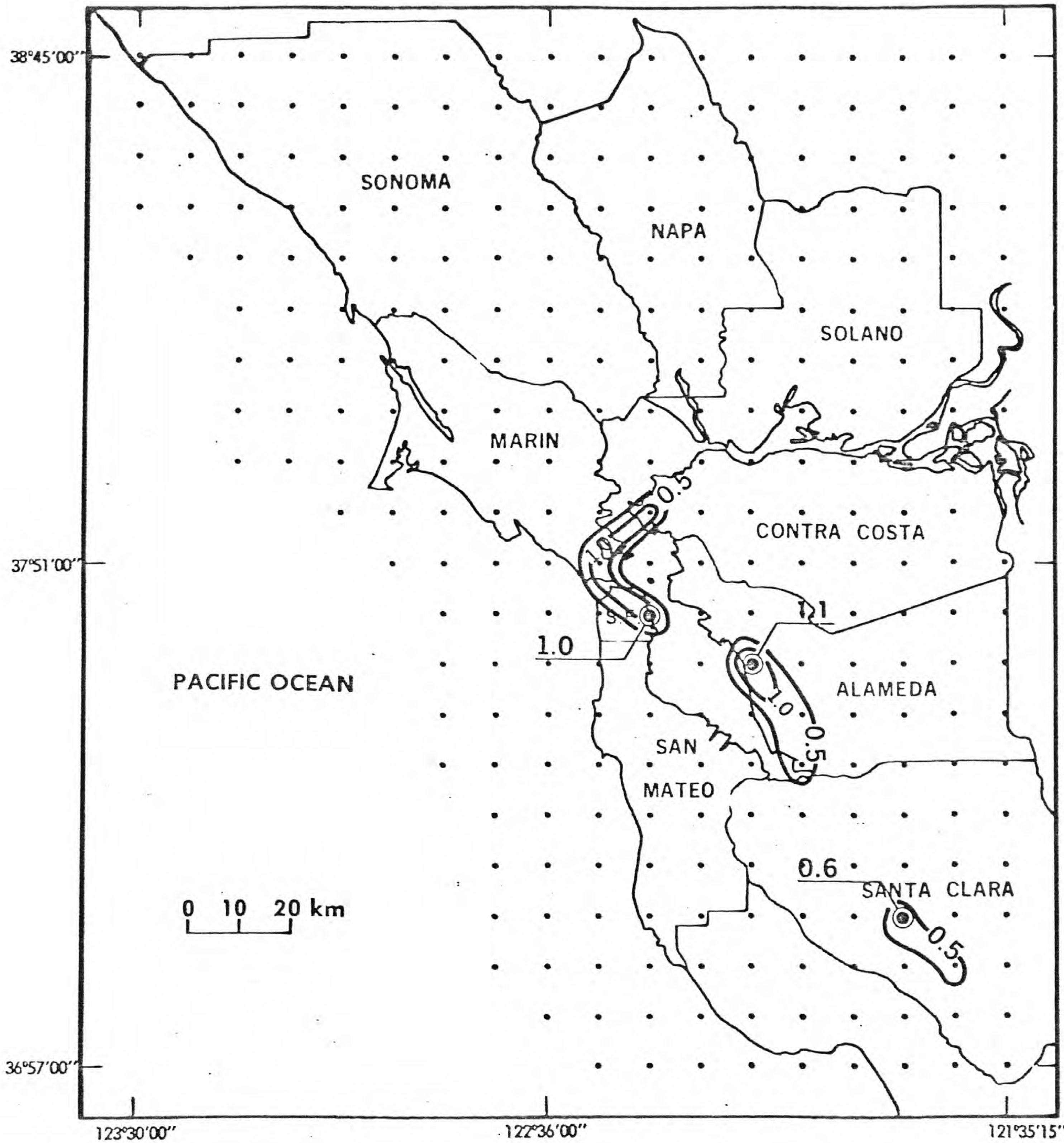

Figure A49.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HA for an earthquake with maximum intensity I_o=VIII.

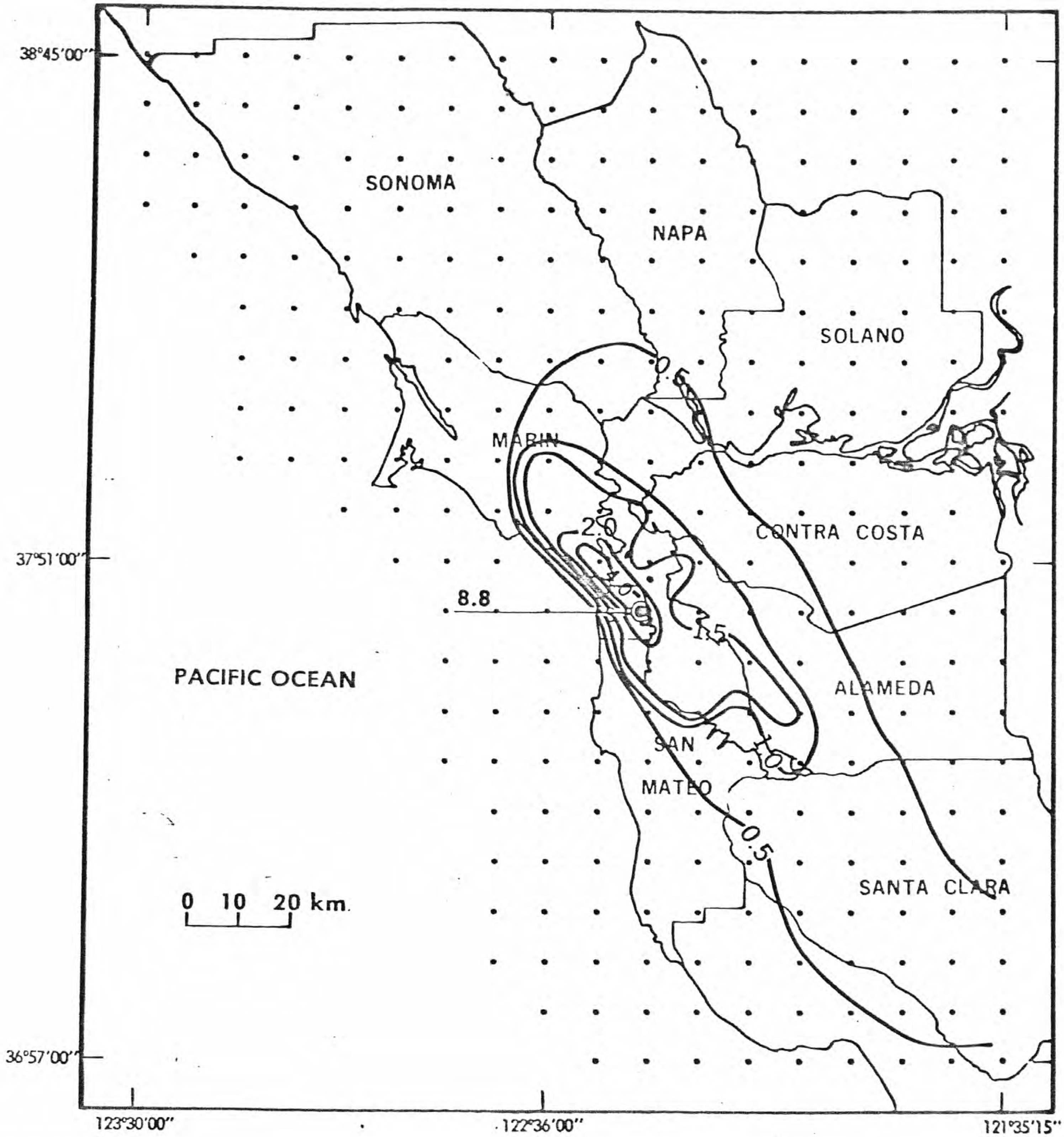

Figure A50.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HB for an earthquake with maximum intensity I_o=VIII.

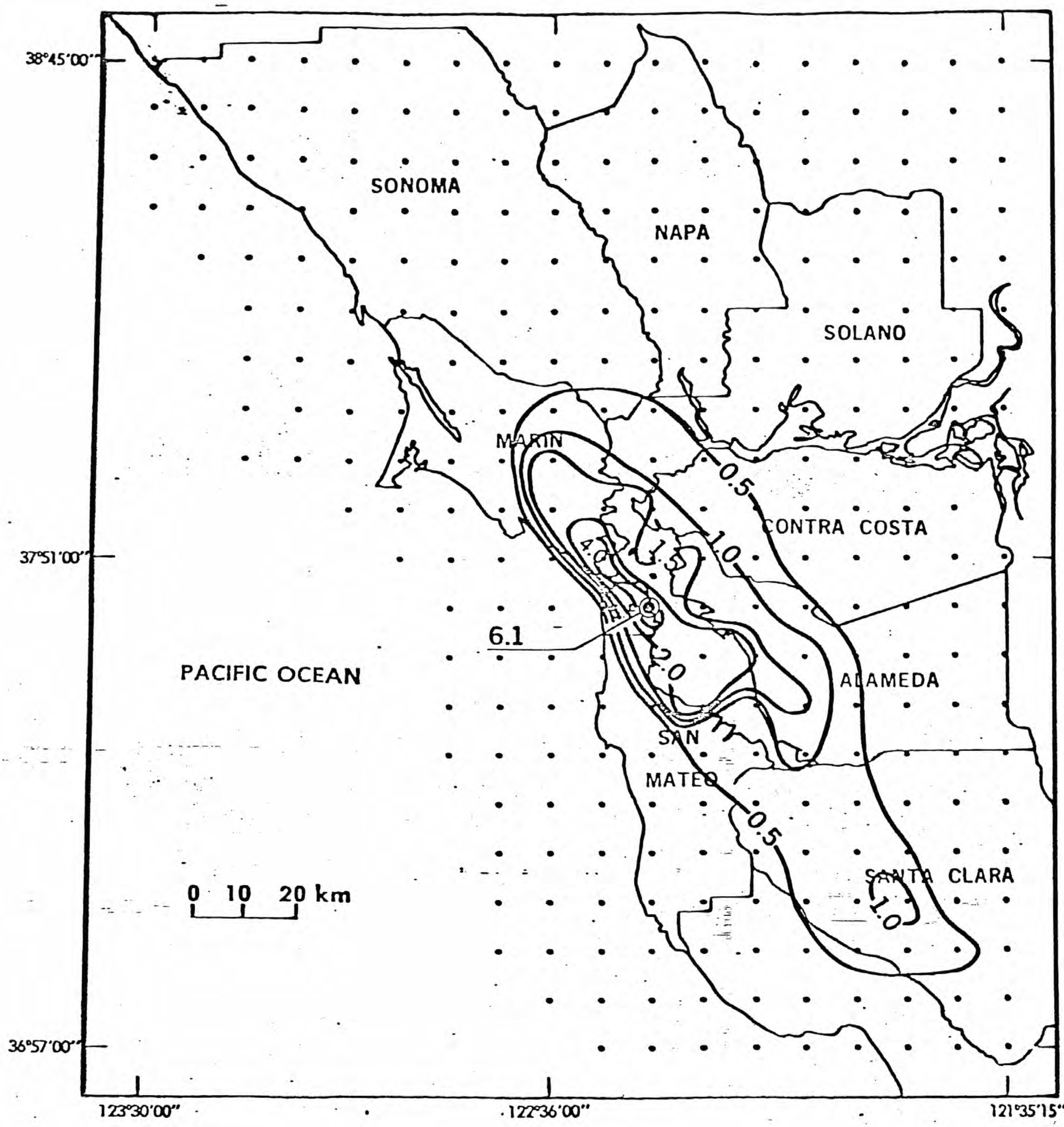

Figure A51.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HC for an earthquake with maximum intensity I_o=VIII.

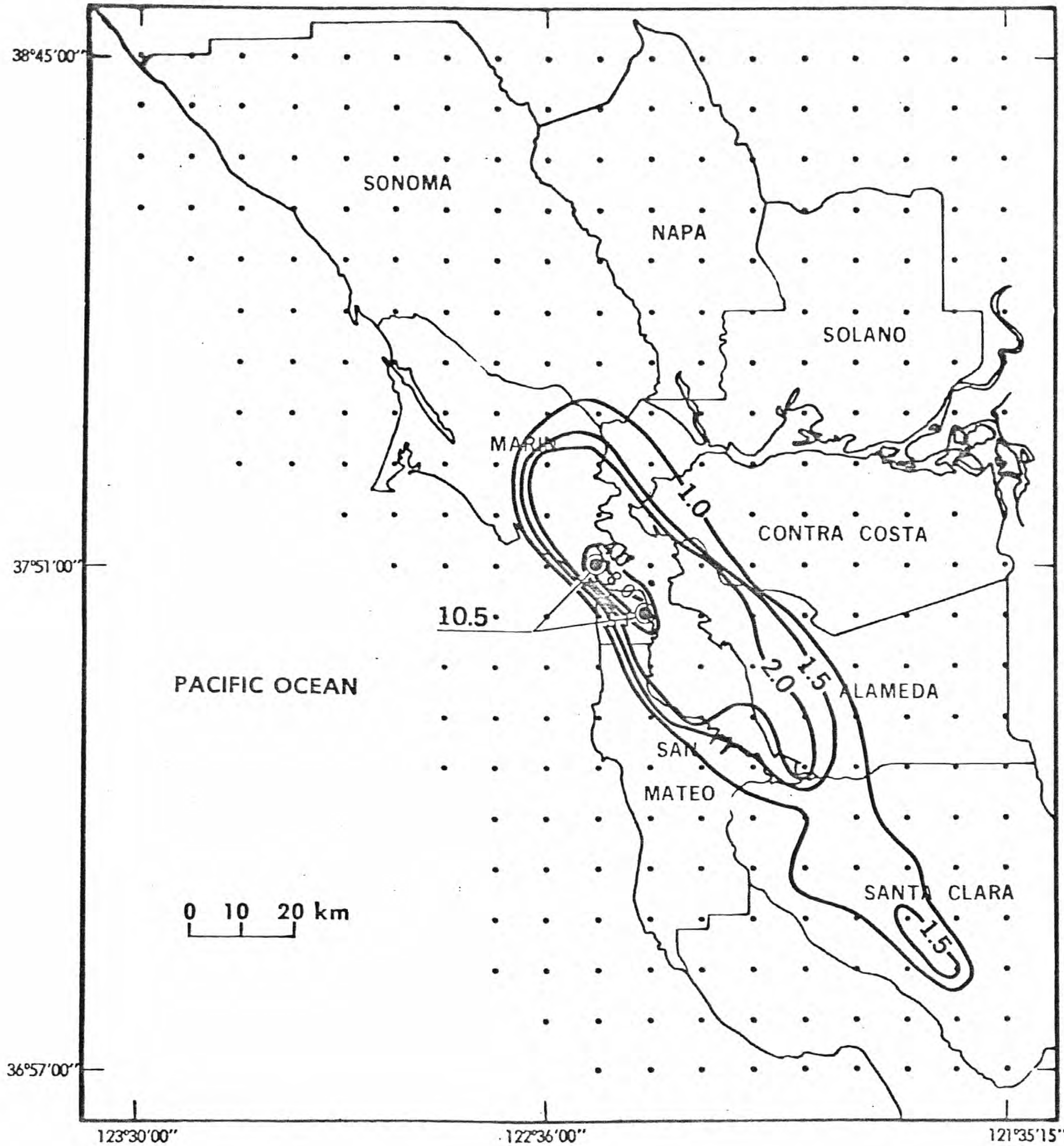

Figure A52.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HD for an earthquake with maximum intensity I_o=VIII.

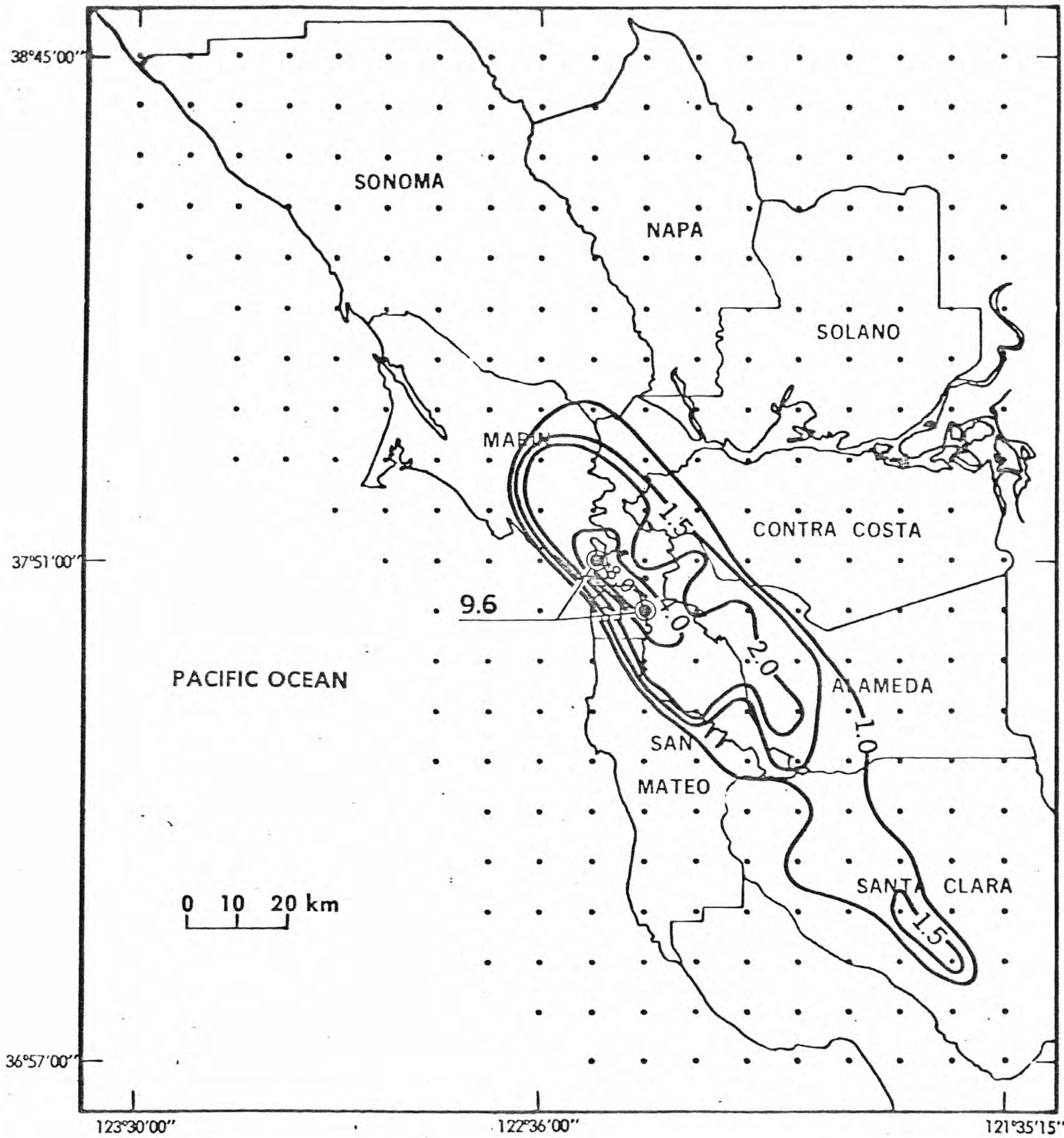

Figure A53.--Percent losses (contours) in the San Francisco Bay area for building subclass 4HE for an earthquake with maximum intensity I_o=VIII.

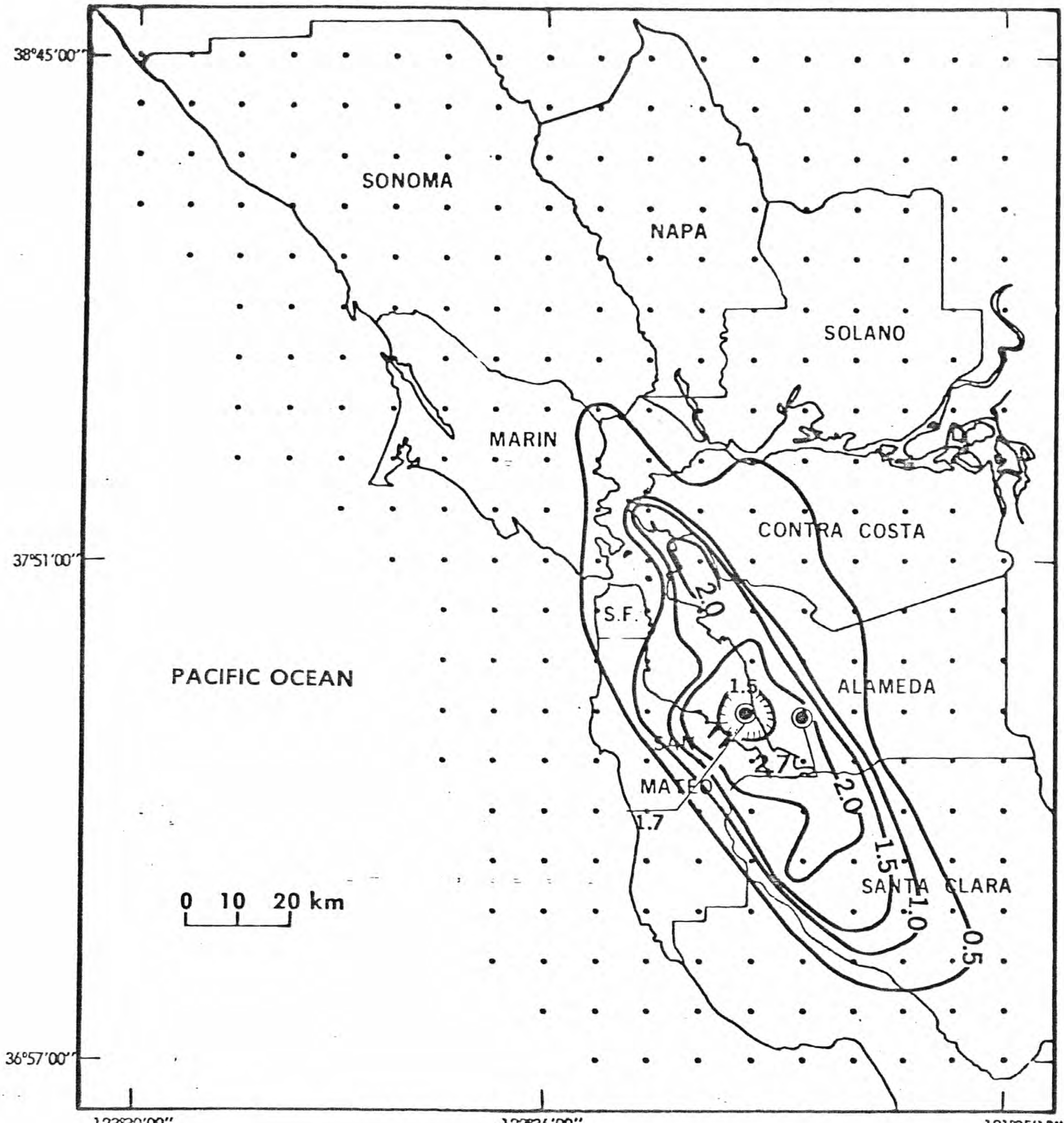

Figure A54.--Percent losses (contours) in the San Francisco Bay area for building subclass 5B for an earthquake with maximum intensity I_o=VIII.

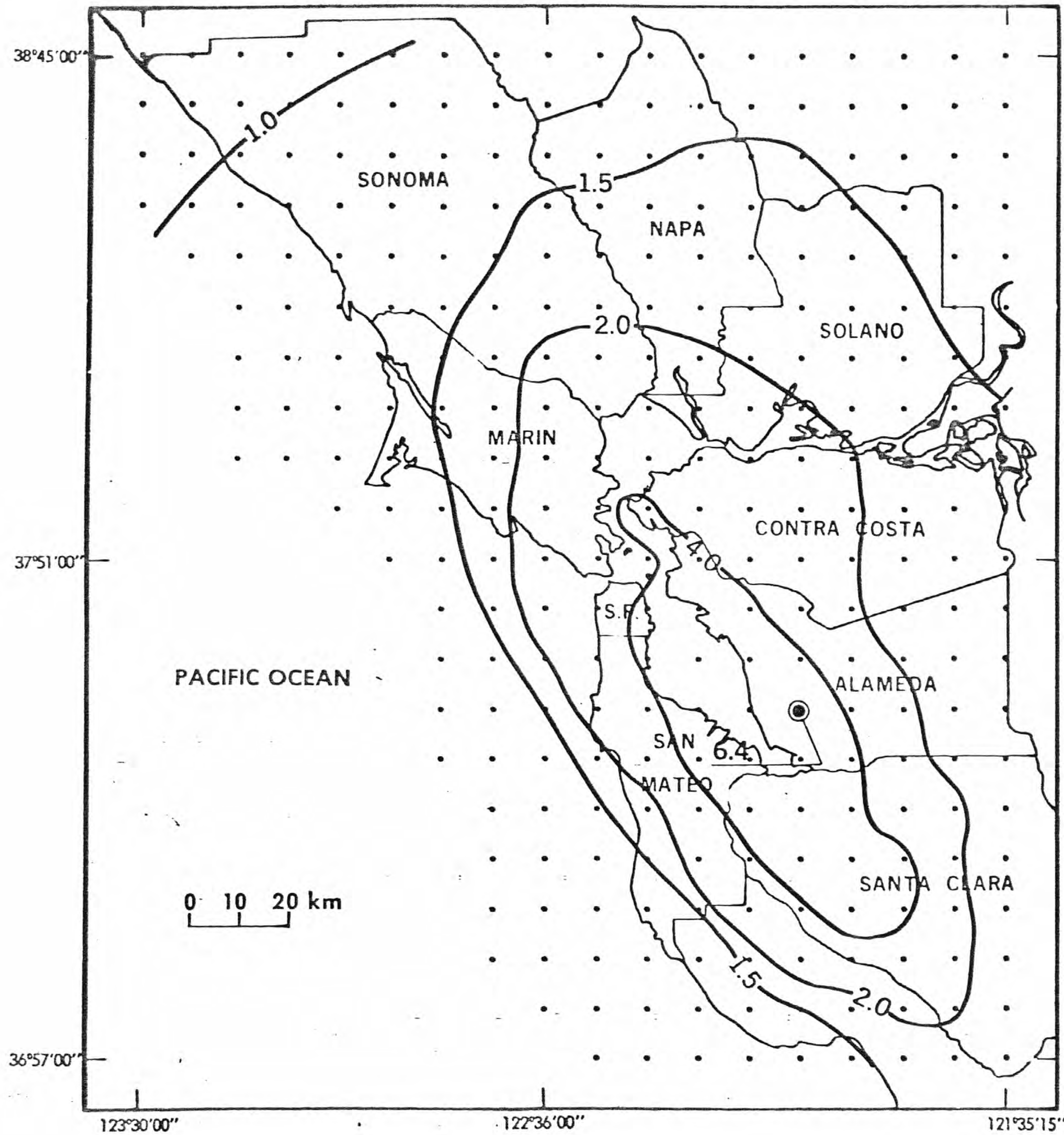

Figure A55.--Percent losses (contours) in the San Francisco Bay area for building subclass 5C for an earthquake with maximum intensity I_c=VIII.

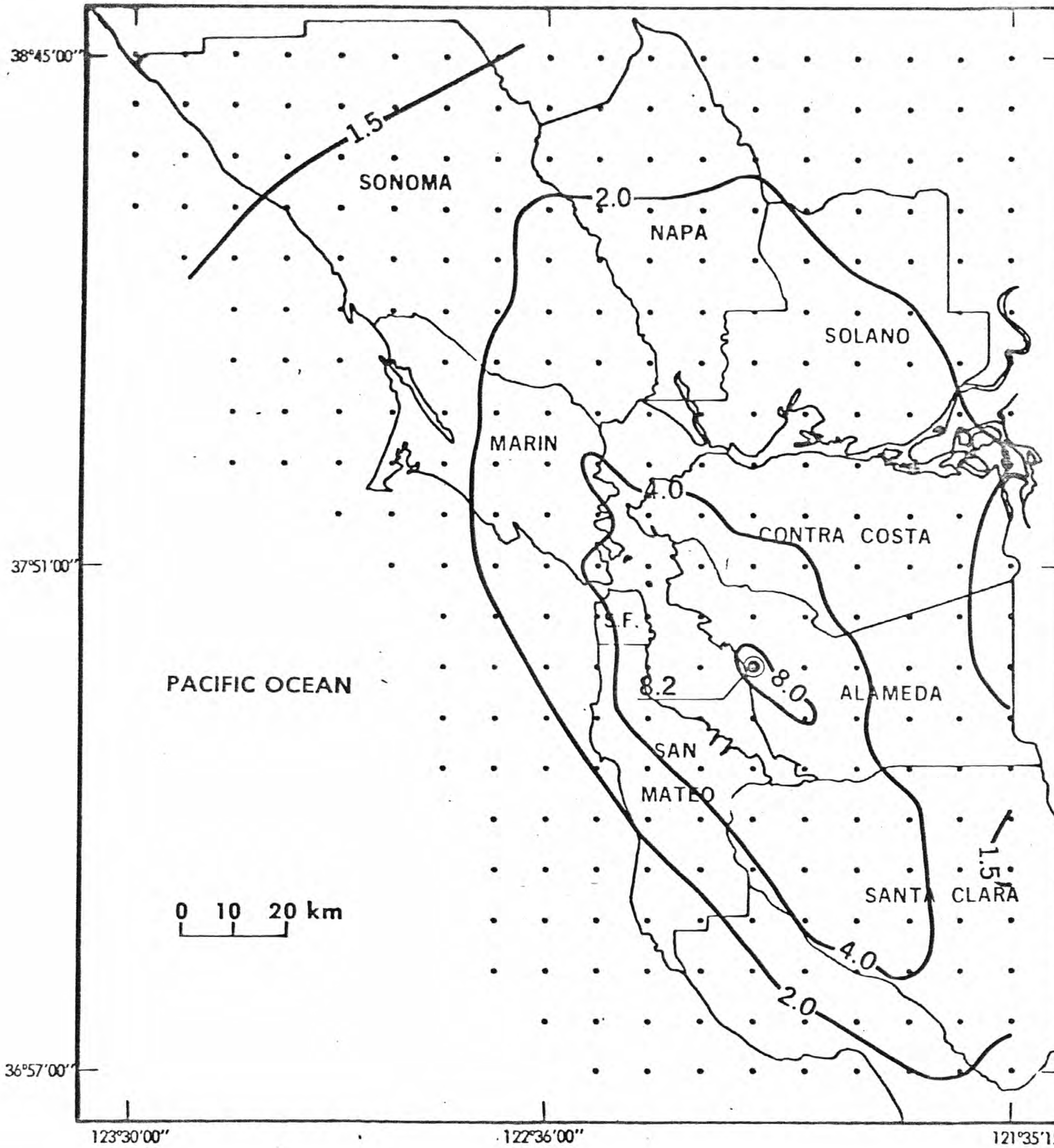

Figure A56.--Percent losses (contours) in the San Francisco Bay area for building subclass 5D for an earthquake with maximum intensity I_o=VIII.

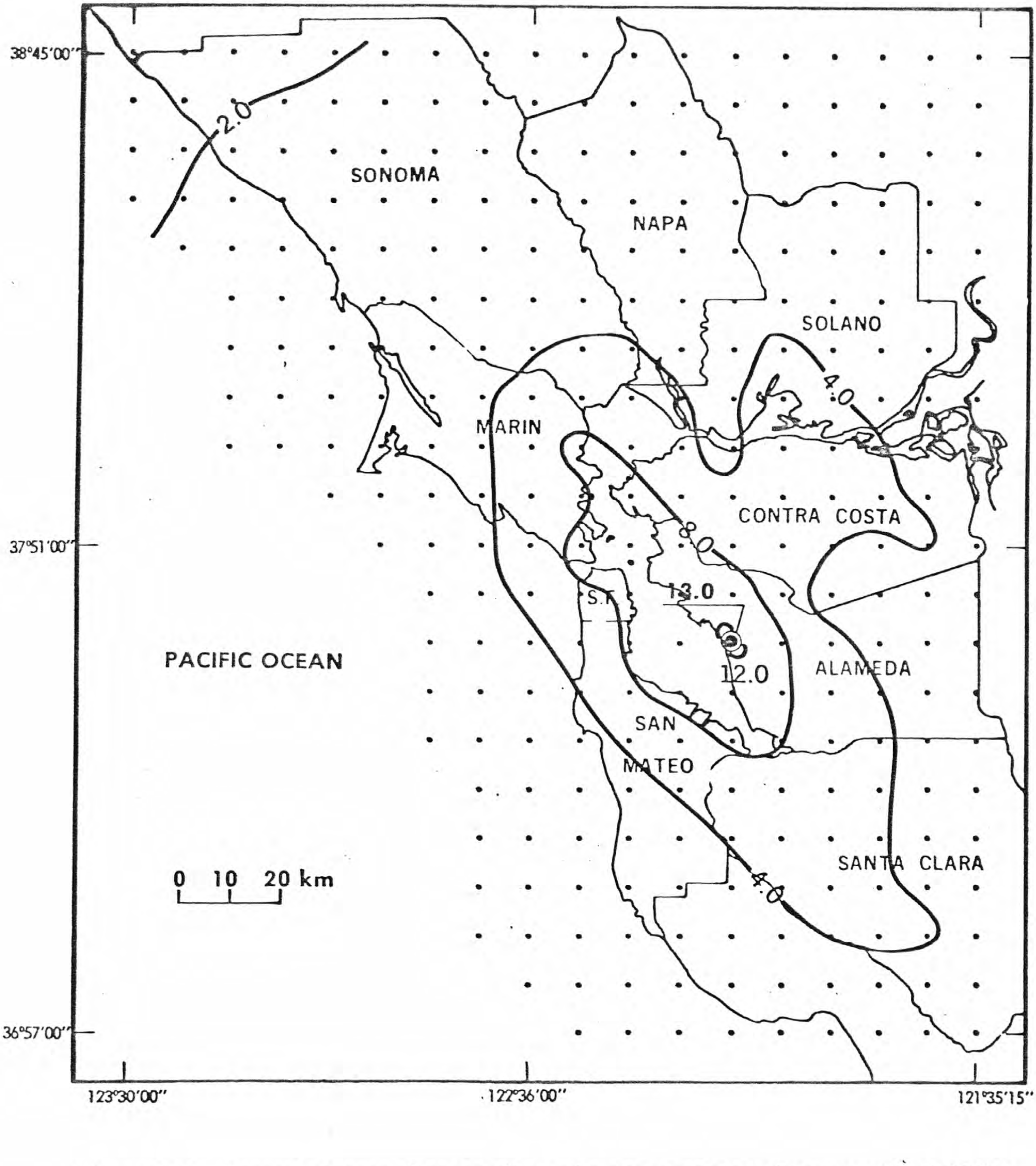

Figure A57.--Percent losses (contours) in the San Francisco Bay area for building subclass 5E for an earthquake with maximum intensity I_o=VIII.