THE LOCATIONAL APPROACH TO SEISMIC RISK MITIGATION: APPLICATION TO SAN FRANCISCO

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SUMMARY

The locational approach to seismic risk mitigation consists of considering alternative sites for a proposed facility, in contrast to considering alternative structural design levels for a fixed site, when faced with seismic hazards in a region. In order to develop this tool for seismic risk mitigation, expected seismic damage to buildings has been incorporated in an urban economic theoretical formulation of urban regions which optimizes location and allocation of production, housing and transportation via linear programming, according to geologic and seismic conditions. This computer program LOCRSK is applied to the Case Study Region of the City of San Francisco, California and shows that the concentration of value in the CBD Financial District (i.e., high rises, etc) is located in an area of high seismic risk. An optimum urban configuration is indicated in which the CBD is shifted slightly westward, to the west of the original shoreline. The approach has three potential applications: (1) optimum planning of new towns in seismic areas, (2) as a guide for a rebuilding policy following major devastation (eg, Managua 1972, Tokyo 1923, San Francisco 1906, Tan Shan 1976), and (3) as input to the continual process of urban development.

INTRODUCTION

The seismic risk of an urban region is the sum of the seismic risk of its individual structures, including any interaction effects, such as post-earthquake fire spreading. The seismic risk of a structure (herein, seismic risk is synonymous with expected damage) has two basic factors: structural and locational. Predominately, approaches to reducing seismic risk have only been concerned with the structural factor, considering the site and associated seismicity, ground characteristics, etc. as given, and not susceptible to variation. Microzonation has only been concerned with the definition and analysis of site characteristics, given the site. Thus, a planning (i.e., alternative location) approach complementing that of structural engineering has generally gone unexplored.

The objective of this research is to develop a methodology for an alternative location approach to seismic risk mitigation in a practical form usable by planners, economists and decision-makers. The viability of this approach has been demonstrated in a theoretical formulation (Refs. 1,2) but this formulation was rather limited for use in a real planning context. The present formulation and computer code is powerful

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and capable of real planning application. For historical and geographical reasons, most urban regions' Central Business Districts (CBD) have developed waterside (i.e., on a river or bay shore) on alluvium or other soft soils which in a large earthquake are subject to long duration strong shaking, ground failure and/or liquefaction. That is, we find a situation where the CBD (i.e., the concentration of highest value) and the entire urban region have been centered over ground which, generally speaking, has the highest damage characteristics. Given this insight, it is intuitively obvious that the building and population densities should be shifted away from ground with higher damage potential, toward ground with lower damage potential, Fig. 1. The question arises, however, how much this shift should be, since the ground condition (and the associated damage potential) varies continuously. The concept of the alternative location approach derives from the field of urban economics (Ref. 3) which permits an economic characterization of an urban region, incorporating such factors as transportation, land development, structure, etc. costs. By incorporating a 'seismic penalty' (i.e., expected seismic damage for each type of structure as a function of location, where the location specifies ground condition and proximity to seismic sources, so that expected ground motion can be estimated) a cost-benefit analysis can be performed, where transportation, land development, structure and expected seismic damage costs can be traded off to determine the population and building density distribution which minimizes the total cost of the urban region, thus obtaining the 'optimum' urban configuration with respect to earthquake damage.

THEORETICAL FORMULATION

Urban economic or location theory attempts to explain the urban form of cities (i.e., the arrangement of structures and support facilities) by applying economic principles. The field made a major advance in the 1960's when the theory of the firm was combined with consumer utility theories by Alonso, Mills, and Muth (Refs. 3, 4, 5) to develop a theory of urban location and land rent (see Richardson, Ref. 7 for an extensive review). These advances resulted in analytic models which solve for an optimal urban configuration (based on consumer preferences and production, land and transportation costs) or solve for an optimal location for a facility within a given area. In the present study, the earlier work of Mills (Refs. 4,7) is used as the basis for developing a linear programming urban location model. The linear programming approach is used because it permits a detailed, realistic, representation of the urban area and an inexpensive analytic solution. The objective function used herein is that portion of the total cost of the urban region which is subject to variations based on changes in location of economic activities in the city (e.g., housing). Minimization of the objective function constitutes minimization of the total cost of "operating" the urban region. When the objective function is formulated without consideration of seismic damage and then minimized, the resulting urban form should replicate the real, existing, present urban form. This is based on the assumption that the existing urban form has developed in an economically rational manner without, however, consideration of seismic damage, building alike on land of good and bad seismic characteristics. When seismic damage is incorporated in the objective function and minimization of this objective function is performed, the resulting urban form is that which should have developed if seismic damage had been considered in an economically rational manner.

The objective function used herein consists of the annual costs of capital (structures), land and transportation, subject to a series of linear constraints. The only dependent variable within the model is the location of production activities within the urban area. By solving the model for the cost minimizing solution, an efficient urban arrangement is determined. The model is solved ignoring seismic damage, and then a solution is obtained taking into account seismic damage potential. The difference between the values of the objective function in these two solutions indicates the value of urban location in mitigating seismic risk. The objective function excluding seismic damage is given in Equation 1), with certain notation specific to the San Francisco Bay Area: MINIMIZE Z =

Land Cost:

$$R_1 \sum_{x,y} \sum_{r,s,b} a_{1rs} \cdot P_{rsb}(x,y) \tag{1a}$$

Capital Costs:

$$+ R_2 \sum_{x,y} \sum_{r,s,b} a_{2rs} \cdot P_{rsb}(x,y) \tag{1b}$$

Transportation - Office:

$$+ K_1 \sum_{x,y} \sum_{r,s} C_1(x,y) \cdot P_{1S1}(x,y) \tag{1c}$$

Transportation - Retail:

$$+ K_2 \sum_{x,y} \sum_{s} C_1(x,y) \cdot P_{2S1}(x,y) \tag{1d}$$

Transportation - Manufacturing:

$$+ K_3 \sum_{x,y} \sum_{s,b} C_b(x,y) \cdot P_{3Sb}(x,y) \tag{1e}$$

Transportation - Commuter

$$+ K_4 \sum_{x,y} \sum_{s} C_1(x,y) \cdot P_{4Sb}(x,y) + K_4 \cdot C_b(CBD) \cdot L_b \tag{1f}$$

The objective function including the seismic damage function is identical to Equation 1 except that the capital cost term (1b) is replaced by term (1b').

$$R_2 \sum_{x,y} \sum_{r,s,b} a_{2rs} \cdot P_{rb}(x,y) \cdot [1 + D_{rs}(x,y)] \tag{1b'}$$

Notation:

The notation "(CBD)" denotes the location of the Central Business District.

x,y = Grid location coordinates

a_{qrs} = Input-output (I/O) coefficients (input of land and capital to produce output of an economic activity, such as an 8 story office). q = Inputs (1 Land; 2, Capital). r = Output (Product) (1, Office; 2, retail; 3, manufacturing; 4, Housing). S = Story or group of stories in which output activity takes place; b = Output destination (1, CBD; 2, Bay Bridge; 3, Golden Gate Bridge; 4, Highway 101 and Interstate 200, ie, Peninsula; 5, Node in which good is produced).

P_{rsb} (x,y) = Level of production of the r^{th} output at node (x,y) on s^{th} story for output destination b.

C_b (x,y) = Effective distance from node (x,y) to output destination b. By effective distance, we mean

R_1 = Annual rental rate per unit area of unimproved land remote from development.

R_2 = Annual real cost of capital.

K_r = Annual cost of transporting the products of a unit area of space devoted to P_r one unit distance-equivalent.

L_b = Specified number of non-resident commuters working in the urban area, entering through node b.

The objective function is minimized subject to a series of production constraints (Equation 3 and land use constraints (Equation 4).

Sufficient Production to Destination Nodes:

$$\sum P_{rsb}\ (x,y) \geq P_{rb} \quad \text{for all r, and b,x,y} \qquad (3)$$

Land Use Constraint:

$$\sum_{r,\ s,\ b} a_{1rs} \cdot P_{rsb}(x,y) \leq A(x,y) \quad \text{For all x,y} \qquad (4)$$

Local Retail Constraints:

$$\sum_{s} P_{4s5}(x,y) \leq mP_{2s5}(x,y) \quad \text{For all x,y}$$

Where:

P_{rb} = Required production of the r^{th} good needed at Output Node b.

A(x,y) = Available land area at (x,y).

m = Proportion of local retail space to housing space.

The minimization solution of the linear model is accomplished using LOCRSK, a new computer program developed in the course of this research.

APPLICATION TO SAN FRANCISCO

The above methodology was applied to the City of San Francisco, as a case study region. San Francisco was chosen due to its high seismicity, variety of soil and building types and concentration of its CBD on seismically poor soils. Due to space limitations, the reader is referred to the full report (Ref. 8) for model parameters and details of the application of LOCRSK to San Francisco. In Fig. 2 is shown a LOCRSK map of structure and occupancy distribution in San Francisco, not considering seismic damage. Note that annual 'operating' costs of the city are \$1.69 billion, and that LOCRSK effectively replicates San Francisco, placing the center of office activity coincident with the specified CBD. To these 'operating' costs should be added seismic structural and contents damage costs of \$312 million per year, arrived at by estimating simple structural damage for each structure, soil and occupancy, and multiplying by 3 to include total damage to contents and occupants (see Ref. 8 for details). Thus, total annual 'operating' costs are \$2.002 billion. Fig. 3 shows the city with the CBD specified at the same location as for Fig. 2, but the structures and occupancies free to seek their seismically optimal locations, which results in a net savings in total operating costs of \$76 million per year, or about 4% due to the locational approach to seismic risk mitigation. Fig. 4a shows the changes in the city land uses, while Figs. 4b and 4c display the LOCRSK feature of "zooming" in on an area of interest, in this case the CBD. Note the relatively minor shifts in land use required to cause a 4% decrease in urban seismic risk. Other applications of LOCRSK, including the opitimization of the CBD location, are given in Ref. 8.

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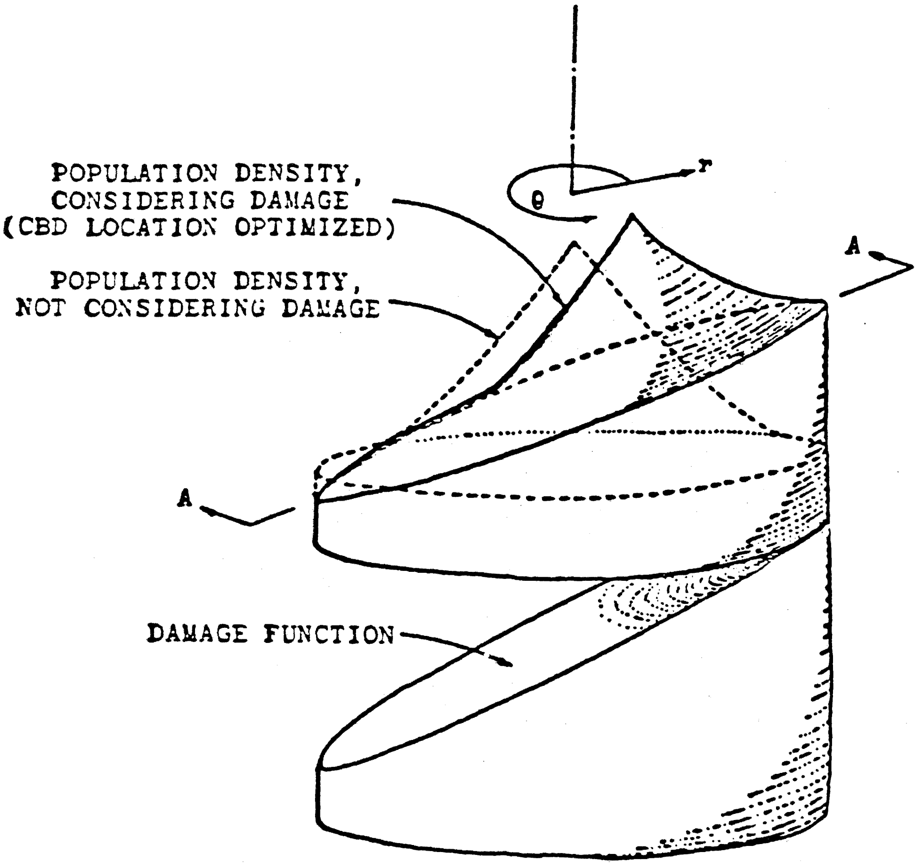

Fig. 1 Sketch showing urban region with oblique plane damage function, axi-symmetric population density resulting when damage is not considered, and non-symmetric population density resulting when damage is considered.

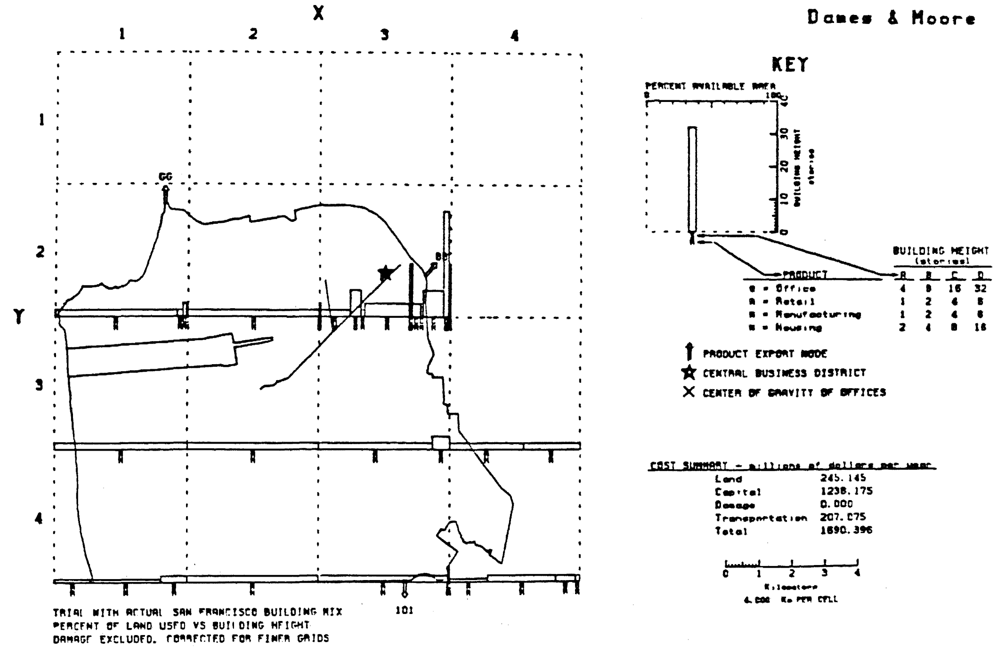

Fig. 2 Structure and Occupancy Distribution in San Francisco "as-is", not considering seismic damage, which adds $312 million per year.

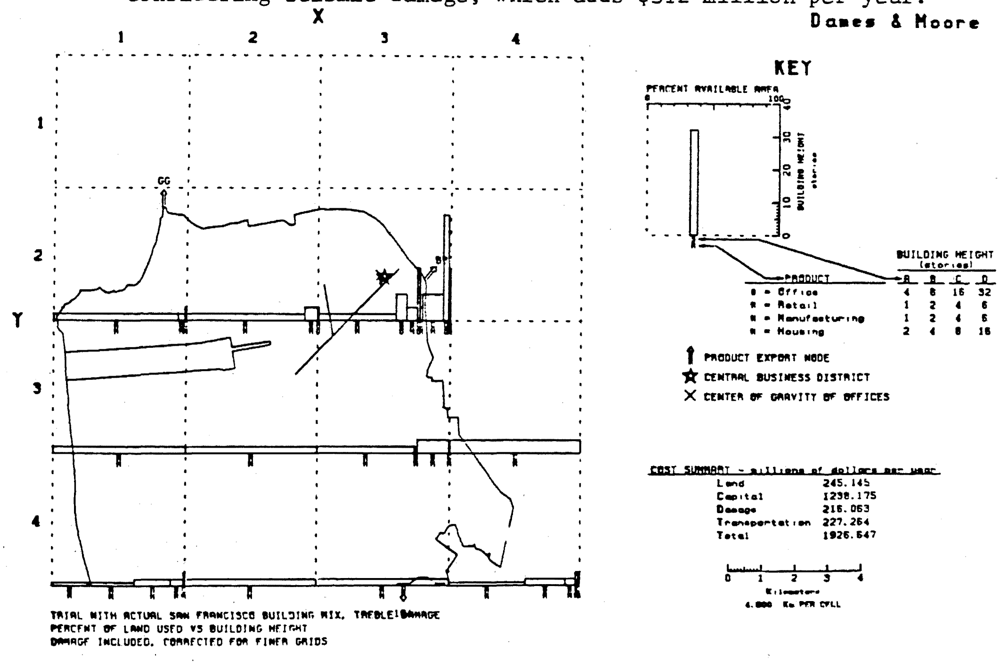

Fig. 3 Similar to above but considering seismic damage. Optimizing structure and occupancy location (but holding same CBD location) reduces annual seismic damage but $76 million, or about 4%.

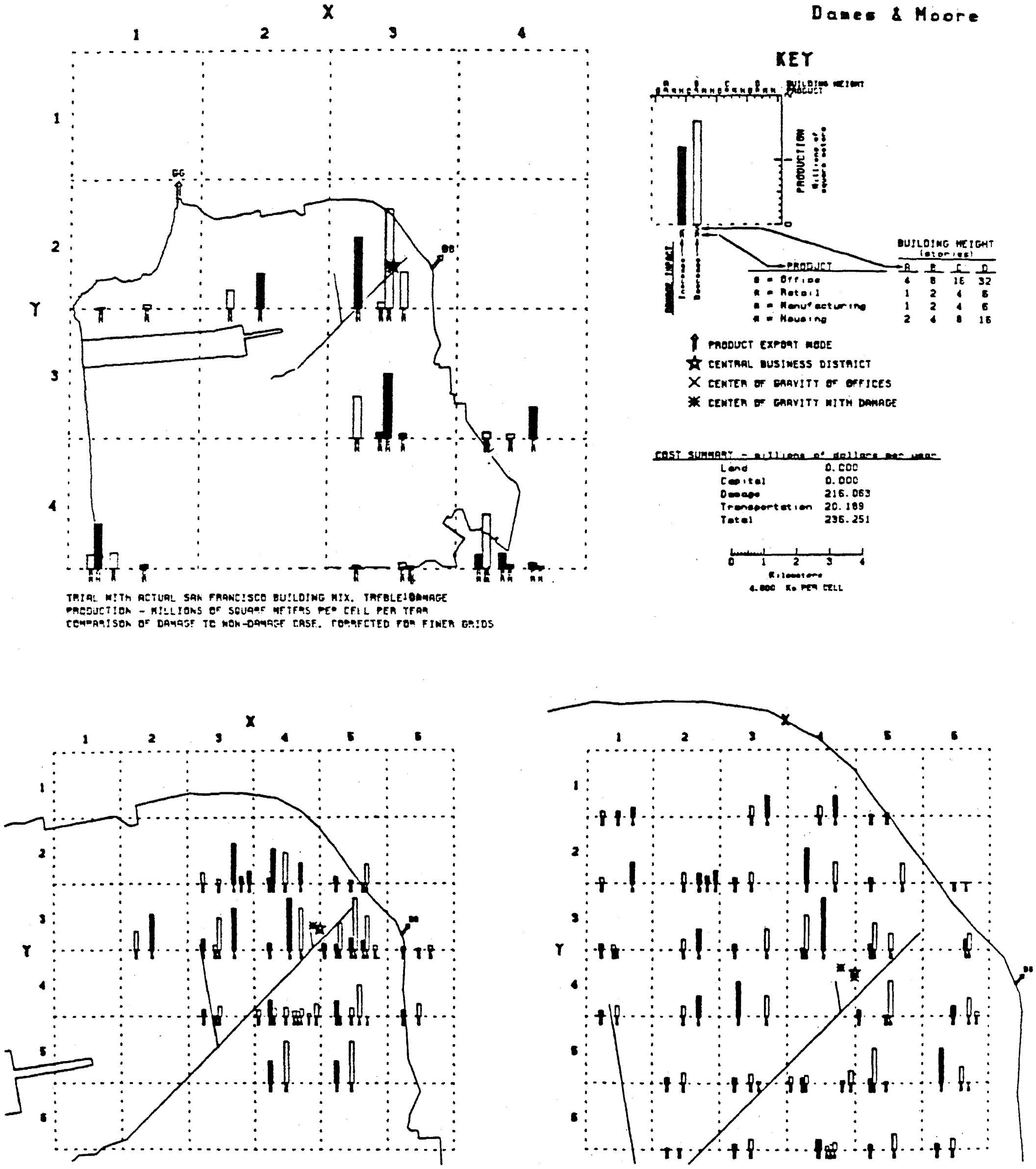

Fig. 4. (a) Upper figure is map of differences in land uses between Figs. 2 and 3(on a 4 km. grid), (b) lower left, shows 4X enlargement of city (1 km. grid), and (c) lower right, shows further 2X enlargement of CBD(0.5 km. grid).