# IDENTIFYING AND MAPPING SEISMICALLY HAZARDOUS HOUSING IN URBAN AREAS

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## ABSTRACT

This paper summarizes a study which developed a method for identifying and mapping seismically hazardous existing housing in urban areas.

The first part of the project developed methods based on photogrammetric techniques for identifying, classifying, and inventorying existing housing structures in hazard-prone urban areas. A computer-based cartographic data system was developed to map existing housing, probable earthquake intensity distribution, soil distribution, and probable levels of damage of housing. The data system allows information derived from aerial photographs to be recorded, graphically displayed, and combined with other cartographic data. Output capabilities include color display maps generated automatically.

The second part of the project defined the seismic vulnerability of prevalent housing types. The purposes of this phase of the study were as follows: (1) to arrive at clear definitions of reference damage states and damage ratios, (2) to assess the expected behavior during earthquakes of key structural elements and connections in the selected housing types, (3) to assess the type and degree of damage expected to individual buildings and to families of buildings during earthquakes of Modified Mercalli intensities VII, VIII, and IX, and (4) to assess certain consequences of damage to housing, such as life hazard and loss of habitability. Construction details for six housing types were first identified, drawn, and summarized. A detailed questionnaire was developed next and distributed, together with the description of the housing types, to fifteen professional engineers. Two follow-up meetings with respondents to the questionnaire were then conducted. Analysis of the questionnaire and meeting results show that the perceptions of engineers about the terms damage ratio and damage state differ widely. Responses for simple rank ordering of housing types, which are not affected by these perceptions, are consistent and believable. Moreover, rank orders derived from normalized damage matrices are in close agreement with rank order responses. Respondents expect a nominally good housing unit to suffer the same damage on soft soil as on firm soil. But a family of buildings is expected to suffer more damage over soft soil than a similar family over firm soil because of soil amplification, pre-existing but unnoticed damage, settlement, liquefaction, and other effects due to the soft soil.

The final part of the project developed maps showing distributions of expected damage to existing housing in the study area. These maps were generated by using the cartographic data system with stored housing inventory data; earthquake hazard data; soils, liquefaction, and ground faulting data; and housing type vulnerability data. Variations in damage patterns due to differences in expected intensity levels across the study area were obtained by an automatic overlay process. Each damage distribution map shows, for clusters of housing, the mean damage ratios expected as a result for an earthquake of known epicenter and magnitude. The locations most vulnerable to disaster effects could therefore be targeted within an urban area. The maps of the type obtained are potentially very useful for a wide range of pre- and post-disaster policy planning purposes.

The study described used housing types and patterns and the soil distribution for the Boston, Massachusetts, U.S.A., urban area, but the methods developed have general applicability to any urban area.

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## INTRODUCTION

A primary difficulty in the development and implementation of policies for mitigating the effects of natural hazards (such as earthquakes and hurricanes) on housing in urban areas is simply that of assessing the probable magnitude of the problem confronted. This same difficulty faces planners who prepare regulations for redevelopment and retrofit of existing housing, and those who develop post-event emergency plans. To obtain quantitative dimensions of the problem, researchers have performed seismic risk studies of ever increasing sophistication over the last fifteen years. A seismic risk study for a region estimates the earthquake hazard, identifies the existing or planned land use, estimates the seismic vulnerability of the natural and manmade units, and assesses the probable damage. The greatest progress to date is in the area of estimating and mapping the hazard (Ref. 1); models now exist to assess in probabilistic terms both the primary hazards of ground shaking and ground faulting and the secondary hazards of liquefaction, landsliding, and flooding. Perhaps because they are not as amenable to rigorous mathematical analysis, less progress has been made in the other areas of seismic risk analysis. This paper explores one way of rapidly acquiring needed inventory data on the housing stock in a hazard-prone urban area, and it discusses methods for making detailed assessments of the overall vulnerability of a community with respect to earthquakes on the basis of this data.

The ultimate goal of the research was to obtain maps of probable earthquake damage to housing. To reach this goal, the following objectives had to be met: (1) provide a method for identifying the range of housing types (from single family units through various types of multi-family buildings) that exist in hazardous urban areas, for inventorying the housing types identified, and for mapping their geographic distribution; (2) assess the relative vulnerability to earthquakes of the housing types found to be prevalent in the hazardous area, and; (3) provide a method for mapping probable housing damage in cities on the basis of mapped distributions of housing types and a knowledge of their relative vulnerability to seismic forces.

The method developed to assess quantitatively the probable damage to housing in an urban area consists of four steps (Figure 1; also, see Ref. 5). The first step is to map the distribution of housing in the study area, the second step is to perform a vulnerability analysis for each type of housing in the study area, the third step is to map the probable Modified Mercalli intensity in the area resulting from a design earthquake, and the fourth step is to combine the data developed in the first three steps into a map of probable damage. The ODYSSEY system handled and displayed the large volume of data generated in the study. ODYSSEY (Ref. 2), a computer based cartographic system, allows one to map the earthquake hazard, the inventory of housing, and the consequent distribution of damage.

## LAND USE

To map the housing in a study area, one must identify the housing types that exist in the area and collect data on the actual housing units. Communities normally contain many housing forms. A closer examination of these forms typically reveals the existence of recurring generic types, particularly in medium and low density ranges. Common in the United States are various kinds of single family, detached two family, and row housing; also common are various forms of low and high rise structures with point access circulation networks or with single- or double-loaded corridors. A range of variants have evolved for each generic housing type due to differences in contextual constraints and local building codes and methods. Types different from those mentioned here are, of course, found in other countries.

A special housing typology was developed to identify and classify housing in urban areas. The classification scheme, which is based on unit access types and unit aggregation morphologies, developed naturally upon studying many aerial photographs of American cities. Common names, such as row housing, are used as convenient and familiar descriptors, but the actual classification scheme is more complex. Once the classification scheme was available, aerial photographs of the study area were analyzed to identify the types, numbers, and distributions of housing units present. The dimensional and feature analysis techniques used are standard in photogrammetry.

Blocks 1, 2, and 3 in Figure 1 display the process of obtaining the inventory of housing. The essential step is the identification of the housing types from aerial photographs; this identification is achieved by a set of correspondence rules that relate a pattern in an aerial photograph to a housing type. The correspondence rules must be complete, in the sense of covering the range of housing in the city being studied, and they must be discriminating, in the sense of allowing a housing type to be identified correctly.

This research established correspondence rules for the six housing types prevalent in Boston, Massachusetts, and performed a detailed photogrammetric analysis of the central portion of Boston. The following are the six generic housing types studied: one- and two-family detached units, "three deckers" (a form of three family, one unit per floor, walk-up building unique to the north-eastern part of the U.S.), row houses, and single- and double-loaded corridor buildings (multiple dwelling units per floor, walk-up and elevator served). To use aerial photography for inventory purposes in another city, a housing classification scheme and correspondence rules apropos to that city would have to be developed.

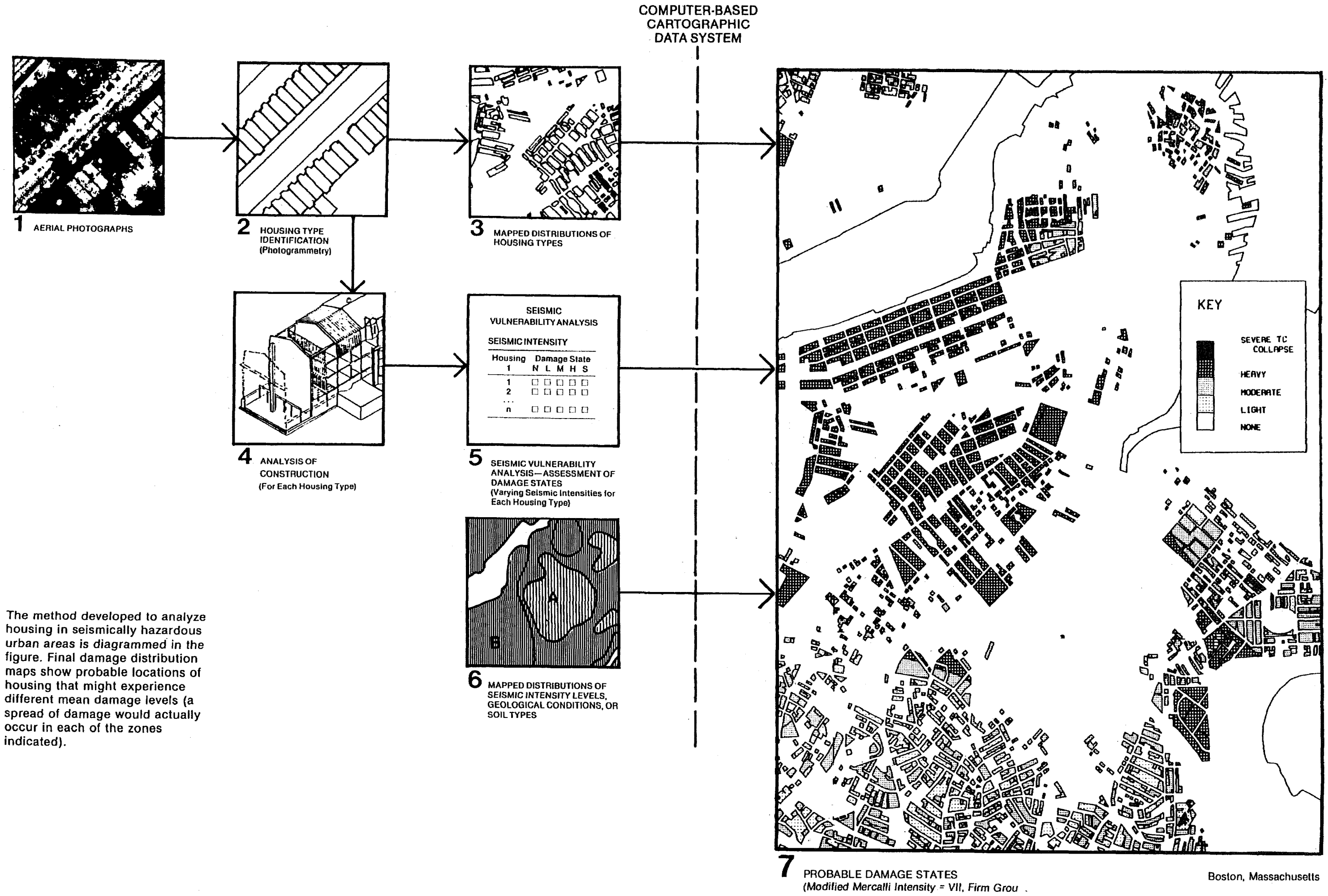
Data gained from the housing type analysis was next mapped. Figure 2 illustrates the type of map generated. The areas delineated are ground coverage areas for different housing types and not individual buildings. This mapping required the gathering, manipulation, and analysis of large amounts of data defining the types and distributions of housing found present in the study area. The ODYSSEY computer-based cartographic system was found useful for these functions. The ODYSSEY system itself is a family of geographic information processing modules. Common file structure, language processor, and other programming utilities provide ease of data transfer from one process to another. The philosophy of the system is the use of sequential files for the processing of geographic data structured on a topological model. The topological approach allows for internal consistency checks on the data and has advantages in performing necessary operations. Analytic work is performed on a topological network structure of boundary intersections (nodes), polygon boundaries (chains), and the polygons themselves.

The research described focuses on existing housing structures, but the methodology is suitable to study other land uses such as buildings and lifelines.

## SEISMIC VULNERABILITY ANALYSIS

The purpose of the seismic vulnerability analysis was to assess the probable seismic performance of housing affected by an earthquake. In a seismic risk study interest centers on the statistical behavior of all the housing units of one type in a city. This statistical behavior is summarized by a Damage Probability Matrix (DPM); an entry in such a matrix gives the conditional probability that a housing unit will sustain a particular Damage State (DS) when subjected to an earthquake of known intensity.

A DPM is conceptually simple. But this simplicity is deceiving because the engineering community has not accepted yet standard definitions of damage states and it has not reached a consensus on the appropriate earthquake intensity scale to use.




The method developed to analyze housing in seismically hazardous urban areas is diagrammed in the figure. Final damage distribution maps show probable locations of housing that might experience different mean damage levels (a spread of damage would actually occur in each of the zones indicated).

FIGURE 1. - Summary of Research Method

None of the available scales of damage states we reviewed appeared adequate for housing. A new scale of damage states appropriate to low-rise housing was defined and compared with published scales (Table 1). The intent was to arrive at a set of objective definitions, but this proved difficult since damage state definitions are inherently subjective. The approach was simple enough: determine the construction characteristics of six housing types, prepare an extensive catalog of individual observable damage instances (e.g. for masonry: localized cracking of joints, localized cracking of masonry, widespread cracking of joints, widespread cracking of masonry, partial collapse of walls, complete collapse of walls), and assign each observable damage instance to one of five damage states labelled "None to minor," "Light," "Moderate," "Heavy," and "Severe to collapse." Thus, each one of the five damage states was defined by a long list of observable damage instances. The damage state descriptions and assignments to damage state categories were later reviewed and revised based on responses to a questionnaire by a number of professional engineers particularly knowledgeable about earthquake damage to housing.

To each damage state one associates a Central Damage Ratio (CDR), and a lower bound and an upper bound Damage Ratio (DR). The CDR is the average of the lower and upper bound DR's for a DS. The DR was defined as the Cost of Repair divided by the Replacement Value of the Structure. One would expect the damage ratios bounding an objectively defined damage state to be objective; in fact, the damage ratios are as subjective as the damage states they bound because the cost of repairs, the replacement value, and the damage states are all inherently imprecise. Repairs to a housing unit damaged by an earthquake normally include work that properly should be labeled maintenance, but a cost breakdown into earthquake damage repairs and other repairs is subjective. Similarly, replacement value may be the market value of the housing unit prior to the earthquake, or the cost of a new unit that replaces the damaged unit in kind.

Information on the seismic behavior of the six residential housing units selected for this study was obtained by means of a questionnaire mailed to fifteen professional engineers, and by two follow-up meetings with the questionnaire respondents. The option of performing detailed structural analyses of each type of housing to predict damage potential was considered and discarded. The primary reasons were difficulty of generalizing results to a family of buildings from one analysis, and the need to obtain nonstructural damage information. The questionnaire was mailed out together with two documents: one describing the overall project to arouse the professional interest of respondents and to induce them to respond, and the other describing the physical characteristics and relevant aspects of construction of the six housing types under study. The construction details shown in the latter documents were obtained primarily from on-site inspections, but they were supplemented by other sources. A three dimensional schematic of a housing type included in the study is reproduced in Figure 3.

The questionnaire was divided into three parts labelled A, B, and C. Part A dealt with establishing definitions of damage states in residential buildings exposed to earthquakes, and with how these damage states relate to considerations such as cost of repairs, the need for inhabitants to vacate the building during repairs, and whether the building should be posted unsafe by a prudent building inspector. The purposes of Part A were to establish precise definitions of the five damage states used and of the damage ratios bounding each damage state, and to obtain information needed for earthquake hazards mitigation planning such as habitability immediately after an earthquake and during repairs. Part B dealt with the probable performance of elements and connections of the six selected housing types during an earthquake of Modified Mercalli intensity VIII. This part helped assess the probable damage of the primary components of subsystems of

TABLE 1. - Damage Ratios, in Percent

| This Study | | Whitman[7] | | Petak and Hart[3] | | Steinbrugge[6] | |
|---|---|---|---|---|---|---|---|
| Damage State | Damage Ratio | Damage State | Damage Ratio | Damage State | Damage Ratio | Damage State | Damage Ratio |
| None to Minor(N) | 0-2 | None | 0-0.05 | None | 0-0.5 | Undamaged | 0-4 |
| Light(L) | 2-10 | Light | 0.05-1.25 | Light | 0.5-1.25 | Slightly damaged | 5-24 |
| Moderate(M) | 10-25 | Moderate | 1.25-20 | Moderate | 1.25-7.5 | Moderately damaged | 25-49 |
| Heavy(H) | 25-50 | Heavy | 20-65 | Heavy | 7.5-65 | Seriously damaged | 50-75 |
| - | - | Total | 65-100 | Very Severe | 65-100 | - | - |
| Severe to Collapse(C) | 50-100 | Collapse | 100 | Demolished | 100 | | |

TABLE 2. - Normalized Damage Matrix

| Damage State | | N | L | M | H | C | |
|---|---|---|---|---|---|---|---|
| Central Damage Ratio -- (CDR) | | 1 | 6 | 17.5 | 37.5 | 75 | |
| Housing Type | | | | | | | MDR |
| 1. Multi-Family | MM VII | 0.19 | 0.31 | 0.26 | 0.24 | | 15.6 |
| Apartment Building | MM VIII | | 0.06 | 0.47 | 0.42 | 0.05 | 28.1 |
| (Double loaded corridor) | MM IX | | | 0.18 | 0.18 | 0.64 | 57.9 |
| 2. Multi-Family | MM VII | 0.15 | 0.27 | 0.25 | 0.31 | 0.02 | 19.3 |
| Row Housing | MM VIII | | 0.04 | 0.40 | 0.33 | 0.23 | 36.9 |
| | MM IX | | | 0.06 | 0.21 | 0.73 | 63.7 |
| 3. Multi-Family | MM VII | 0.21 | 0.35 | 0.37 | 0.07 | | 11.4 |
| Three-Decker | MM VIII | 0.03 | 0.23 | 0.44 | 0.25 | 0.05 | 22.2 |
| (Detached) | MM IX | 0.02 | 0.14 | 0.18 | 0.37 | 0.29 | 39.6 |
| 4. Multi-Family | MM VII | 0.33 | 0.22 | 0.41 | 0.04 | | 10.3 |
| Three-Decker | MM VIII | 0.01 | 0.12 | 0.38 | 0.44 | 0.05 | 27.6 |
| (Semi-Detached) | MM IX | | 0.03 | 0.17 | 0.37 | 0.43 | 49.3 |
| 5. Two Family | MM VII | 0.39 | 0.43 | 0.18 | | | 6.1 |
| Housing | MM VIII | 0.05 | 0.41 | 0.48 | 0.06 | | 13.2 |
| | MM IX | 0.01 | 0.17 | 0.37 | 0.43 | 0.02 | 25.1 |
| 6. Single Family | MM VII | 0.55 | 0.43 | 0.02 | | | 3.5 |
| Housing | MM VIII | 0.17 | 0.38 | 0.45 | | | 10.3 |
| | MM IX | 0.01 | 0.21 | 0.39 | 0.39 | | 22.7 |

TABLE 3. - Mean Damage Ratios, Mean Damage States, and Rank Ordering

| Housing | Housing | Earthquake Intensity | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MM VII | | | | MM VIII | | | | MM IX | | | |
| Type | Identification | MDR(%) | MDS | RankA | RankB | MDR(%) | MDS | RankA | RankB | MDR(%) | MDS | RankA | RankB |
| 1 | Multi-family | 15.6 | M | 2 | 2 | 28.1 | H | 2 | 2 | 57.9 | C | 2 | 2 |
| 2 | Row housing | 19.3 | M | 1 | 1 | 36.9 | H | 1 | 1 | 63.7 | C | 1 | 1 |
| 3 | Three-decker, detached | 11.4 | M | 3 | 4 | 22.2 | M | 4 | 4 | 39.6 | H | 4 | 4 |
| 4 | Three-decker, semi-detached | 10.3 | M | 4 | 3 | 27.6 | H | 3 | 3 | 49.3 | H | 3 | 3 |
| 5 | Two family | 6.1 | L | 5 | 5 | 13.2 | M | 5 | 5 | 25.1 | H | 5 | 5 |
| 6 | Single family | 3.5 | L | 6 | 6 | 10.3 | M | 6 | 6 | 22.7 | M | 6 | 6 |

Rank A computed from MDR
Rank B obtained directly from respondents

the buildings. The purposes of Part B were to obtain information on the behavior of specific elements of the buildings and general damage descriptions for each housing type. Part C was designed to elicit comparisons of the probable seismic behavior of housing under earthquakes of Modified Mercalli intensities VII, VIII, and IX, and to obtain the relative behavior of the six housing types by means of rank orders.

The Modified Mercalli intensity scale (MMI 1956 version described by Richter, Ref. 4) was chosen as the reference for seismic intensity despite its known shortcomings and the risk of using a circular definition; we concluded that even though MMI may not be a good descriptor, it is the best one available. The historical record of earthquakes in the United States is expressed primarily in terms of MMI; therefore, MMI is the only descriptor of earthquake intensity that has an observational basis. Also, many studies performed to date on the damage suffered by structures during earthquakes use MMI as the intensity measure. Since the Modified Mercalli scale is based on observations made during actual earthquakes and many of these observations are unrelated to building damage (e.g., difficult to stand), one may assign to a region an MMI based on all observations except those for one particular type of housing, and then observe the damage to that type of housing.

The opinions of the respondents relative to probable damage to housing are summarized in a Normalized Damage Matrix (NDM, Table 2). An entry i, j of this matrix gives the fraction of respondents, corrected according to the confidence they expressed in their response, who believe that a housing unit will suffer Damage State DS(i) when an earthquake of intensity I(j) occurs. Conceptually, the NDM embodies the spread of opinion of the respondents with respect to the most likely damage state a building will suffer under a given intensity of earthquake. The NDM is analogous to the Damage Probability Matrix, but both matrices are arrived at differently. The product of the Normalized Damage Matrix for a housing type and the vector of Central Damage Ratios gives a vector of Mean Damage Ratios (MDR). For each housing type, an entry MDR(j) is the relative damage we assigned to that housing type when subjected to an earthquake of Modified Mercally intensity I(j). Rank ordering the housing types by decreasing MDR(j) thus gives the relative vulnerability of housing due to an earthquake of intensity I(j). The questionnaire also asked respondents to rank order the housing types. The responses for rank ordering housing according to expected earthquake damage showed a small spread among respondents. The MDR's and corresponding rank orders computed from the Normalized Damage Matrix (Rank A), and the average rank orders given directly by respondents (Rank B) are reproduced in Table 3; the consistency in rank order results is remarkable. The consistency gives credibility to the methodology for obtaining the Normalized Damage Matrix and the resulting Mean Damage Ratios.

## DAMAGE DISTRIBUTION MAPS

Maps of earthquake hazard and housing distribution and the information on seismic vulnerability of housing form the data which are combined to generate damage distribution maps. At a location in a city there exists a probable earthquake intensity (obtained from the seismic hazard analysis), a type of soil (that modifies the earthquake intensity computed for firm ground), a propensity for soil liquefaction and for ground faulting, and a particular type of housing. With this information and the relationships between housing and earthquake induced damage one can compute for each location in the city the mean damage ratio following a seismic event of specified intensity. A map of MDR's thus highlights areas of a city with housing expected to suffer greater damage, but it does not show the spread of damage, nor the damage necessarily occurring at each location. The map areas delineated are ground coverage for different housing types and not individual buildings. Maps of predicted mean damage are useful for disaster response planning and for planning seismic retrofit and land use.

Individual buildings can be mapped for smaller regions of a city identified as specially hazardous. Monte Carlo techniques can then be applied to the available information to map damage scenarios.

The cartographic data base is contained in ODYSSEY files of housing distribution, intensity levels, and soil distribution. The relationships between housing type, earthquake intensity level, and mean damage ratio are contained in value files. Relating the polygon files to value files allows damage distribution maps to be generated.

## CONCLUSION

This paper presents techniques used to identify and map seismically hazardous housing areas. The approach adopted was to look at the seismic performance of families of buildings. This approach allowed one to reach the goal of quantifying the magnitude of the earthquake problem confronted by a community. With this knowledge planners can develop on a rational basis policies concerning post-earthquake response measures and policies concerning new building construction and existing building retrofit.

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FIGURE 2. - Map of Housing Type Distribution

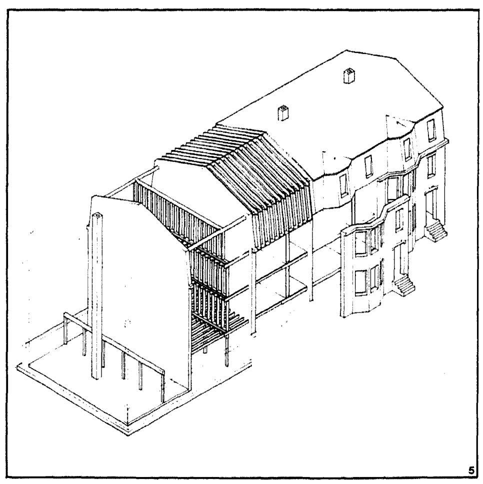

FIGURE 3. - Sample of Schematic Drawing of Housing Type