「한국 시스템다이내믹스 연구」 제7권 제1호(2006.5) : 213-228

Building safe communities: A dynamic simulation study

Cho, Sungsook* · David F. Gillespie** · Karen Joseph Robards***

Abstract

This paper reports the results of a study designed to understand and facilitate disaster mitigation for communities located in low frequency/high magnitude earthquake zones. The study is based on a small town located near the New Madrid Fault Zone and is therefore at significant earthquake risk. A system dynamics model describes the variables and policies governing the distribution of building safety over time. Data from this town is used to establish a 25-year baseline. Simulations are run to demonstrate the consequences of different building policies.

Keywords: Disaster mitigation, safe community, dynamic structure, system dynamics modeling

* Washington University-St. Ph.D. Candidate (제1저자, scho@wustl.edu)
** Washington University-St. Professor (davidg@wustl.edu)
*** Washington University-St. Accreditation Specialist (krobards@cswe.org)

Ⅰ. Introduction

Making our communities safe from disasters is difficult because during periods of stability safety is generally not considered a major concern in most communities. People are reluctant to spend extra money for protection against uncertain risks, and phasing in improvements takes a long time (Gould, 2002). These difficulties are magnified in communities located in low-probability/high-magnitude disaster zones. In such zones there are few disasters, and experience with damaging disasters predates anyone currently living. Under these conditions, simulation modeling offers a way to help clarify the likely consequences of various mitigation initiatives.

All levels of government are - or need to be - active participants in disaster mitigation efforts. Mitigation approaches in particular require active promotion by lower levels of government, with the states often delegating authority related to land use to local levels (Rossi, Wright, Weber-Burdin, 1982). Thus, in many ways, local governments are kingpins in planning and implementing activities and programs related to disaster mitigation as well as supplying first responders, although federal and state governments are indirectly involved in safety actions of the community (Gillespie & Robards, 2000).

Government involvement in disaster efforts is critical. However, community safety is not under the jurisdiction of any one group of stakeholders. A focus on one set of stakeholders such as local governments distorts community policy ramifications. Stakeholders for disaster mitigation include those in the commercial and non-profit sectors as well as local government emergency and planning officials. The overall level of safety in a community is affected by what happens collectively, indicating that the community level of analysis is crucial.

The purpose of this study is to identify the process responsible for the community's level of safety and to reveal the consequences of that process by experimenting with policy parameters. To achieve this purpose we developed a dynamic simulation model of seismic building safety in a small to median-sized communities in population. Our purpose responds to Mileti's (1999) suggestion to study the systemic, interrelated nature of disaster mitigation. The model developed for this study represents a broad, community-level picture of building safety.

The paper is structured into four sections. First, we describe our methodology - including site selection, data collection, time horizon, and analysis. Second, we describe a simulation model of community building safety. Third, we report our findings. Finally, we draw conclusions from our findings, point out limitations of the research, and provide recommendations for research that is needed.

Research Methods

This study considers ways of improving the level of safety in communities. Specifically, we focus on small to medium sized communities with populations of 10,000 to 100,000 located in seismic zones with low-probability/high-magnitude earthquake risk in the United States. The fact of a low probability for an earthquake in these zones acts as a constraint on mitigation resources. The main reason for focusing on a community of this size is that many communities fall into this category. For example, approximately 42 percent of the people in Illinois live in these cities. Census Bureau data identifies 196 communities in the state of Illinois as of July 1, 2002 under this category (United States Census Bureau, 2003). Within this category, a statistically median-sized community in the state of Illinois (United States of America) located near the New Madrid Seismic Zone was selected. The Illinois Emergency Management Agency recognizes this community as a leader in the implementation of building codes and concern about seismic safety.

Both archival and interview data were collected. Archival data included Census figures, the identification of buildings and their corresponding contact information, and estimated life safety risk levels of commercial buildings. Data were collected through a survey of building safety and semi-structured interviews with key informants in the community. Eleven semi-structured interviews were conducted with fourteen decision makers including six from the city government, two from the local hospital, three from the public schools, and three from the university located in this community.

The data were collected to represent a 25-year period of time from 1981 to 2005. This time horizon was selected for three reasons. First, during this time period the community experienced an earthquake-related event, namely, the Iben Browning 1990 pseudo-scientific earthquake prediction that generated significant concern and publicity about earthquakes (Farley, Barlow, Finkelstein, & Riley, 1991). Second, the 25-year period is sufficiently long to establish reliable trend lines of building safety and yet recent enough that current policy makers might find the results useful in considering possible policy changes. Third, this time period is recent enough to reliably trace back the information needed and gather perceptual data from key informants.

In this research, safety is defined as the life-safety risk associated with the buildings. We used a survey of building safety, which includes commercial buildings considered essential to disaster response (e.g., police stations, fire stations, hospitals, and schools) (French & Olshansky, 2000) and some large multi-family buildings, health clinics, and large commercial buildings (Olshansky, Wu, & French, (2002).

Each building was measured using the ATC-21, a rapid visual screening assessment index developed by the Applied Technology Council with a grant from the Federal Emergency Management Agency (Olshansky, 1995). It is a method of quickly estimating whether a building is seismically safe and is useful in preliminary community planning. The ATC-21 scores are related to the probability of building collapse and thus life safety. The ATC-21 yields values of 0-6, with 0 as unsafe and 6 as safe. Based on these ratings, our model distinguishes three primary levels of safety: unsafe buildings (with scores of 2 or less), moderately safe buildings (with scores of 3 or 4), and safe buildings (with scores of 5 or 6) (Olshansky et al., 2002).

Using the data described above, we developed a dynamic simulation model of three levels of safety. Dynamic simulation modeling helps us understand the distribution of safety over time and also facilitates experiments by allowing modification of policy parameters to explore the potential impact of such changes (Gillespie, Robards, & Cho, 2004). System dynamics, in particular, emphasizes the feedback processes that determine the level of safety over time (Sterman, 2000). The model was created in Vensim PLE Plus, Version 5.5d (Ventana Systems, Inc. 2005). This process is described in more detail in the following section.

A Dynamic Simulation Model of Community Safety

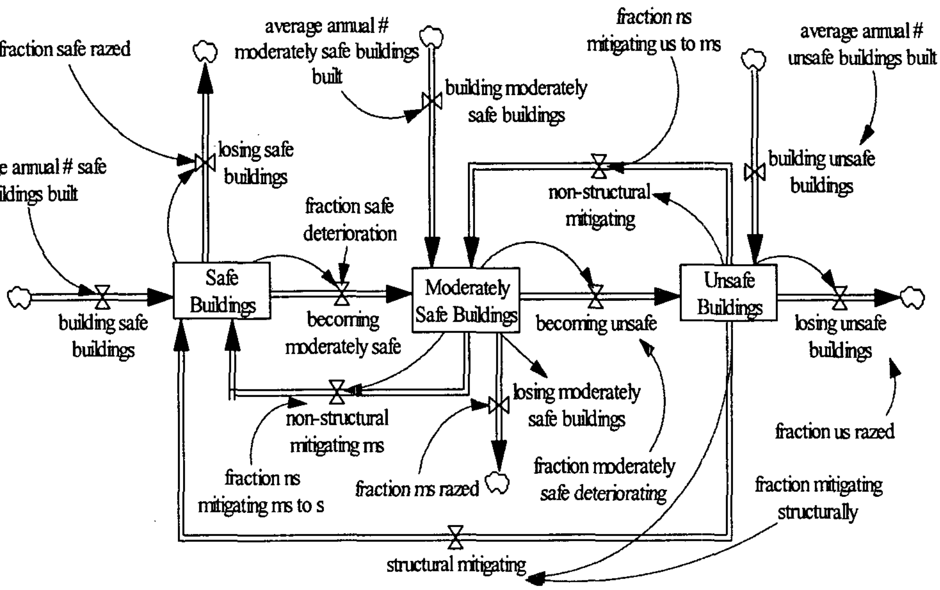
In this study, we focus on ways of expediting the level of building safety in the community. Although the level of building safety has been increasing over the past 25 years, it remains unsatisfactory because essential facilities are key components in responding to disasters events. The community strengthened its building code in 1987, which has helped to increase the level of safety of the essential facilities. However, the building code applies only to new buildings. With the right policy in place for new buildings, we focus on mitigation and demolition activities as the next reasonable steps to increase the community's overall level of safety.

Our model represents the distribution of building safety over time and factors that influence that distribution. The model was initialized (variables were given numerical values) using data about building safety levels from the ATC-21 survey, along with information regarding the various rates of construction, building deterioration, and mitigation. During the 1981-2005 time period the city built an average of about 5 new essential facilities (buildings) each year, structurally mitigated 1 building, and non-structurally mitigated 16 buildings. For the same time period an average of 18 safe buildings, 17 moderately safe, and 7 unsafe buildings were demolished.

The mitigation process is structured around a chain of three variables, also called "stocks" or variables that accumulate: safe, moderately safe, and unsafe buildings. In system dynamics modeling, this structure is referred to as a "conserved flow" or "main chain infrastructure" (Richmond, 2000). It is a conserved flow because any given building for the life of its existence can be in only one of these stocks at a time. Taken together these three stocks represent the community-wide distribution of building safety. Based on the ATC-21 measures, every building in the sample is safe, moderately safe, or unsafe with respect to the area's earthquake hazard.

Over time, the levels of safety change for individual buildings and for the aggregate of buildings in the community. Various actions change the level of building safety. There are three ways to increase the number of safe buildings: by building new buildings to the most current building code, by structurally mitigating existing buildings, and by non-structurally mitigating existing buildings. Structural mitigations are major, expensive and usually internal modifications to buildings, such as tying walls and ceilings together or reinforcing joints. Non-structural mitigations are less costly; examples include bolting bookcases to the walls or strapping hot water heaters to walls to prevent them from falling over. Both are important mitigation strategies that can prevent harm to people and property damage in the case of an earthquake.

There are also three ways to decrease the number of safe buildings: by doing nothing (physical deterioration over time), by planned destruction such as razing for development, and by un-planned destruction such as fire or disaster. In addition, buildings may move between the stocks of buildings; for instance, buildings may start safe and over time become less safe, or start unsafe and become moderately safe or safe. Figure 1 is a stock and flow map showing the actions that cause changes in the community-wide distribution of building safety.



[Figure 1] Stock-Flow diagram of Building Safety

The model for this study was validated through an assessment of its boundary adequacy, dimensional consistency, parameter adequacy, and behavior reproduction (Ford, 1999, pp. 285-288). The assessment of boundary adequacy involved a determination of relevant variables being included and irrelevant variables being excluded from the model. The boundary was deemed adequate when the variables and relationships governing safety and economic development were judged complete. Dimensional consistency refers to equal measurement dimensions on both sides of the equations throughout the model. To test parameter adequacy, we examined the model to ensure that its parameters conformed to activities in the community. This test involved comparing model parameters with the corresponding community policies. The test of behavior reproduction examined the degree to which the model reproduces the distribution of safety over the baseline period. Appendix A reports the full set of model equations.

Mitigation Policies

This simulation model is based on policies existing during the initial study period, 1981-2005. During the first 10 years of this period the building codes did not include seismic provisions. Seismic provisions were first introduced in 1987 and with the adoption of those codes the city began to build only safe buildings. Prior to 1987 the community had build 29 safe buildings, 23 moderately safe buildings, and 2 unsafe buildings. From 1990 on only seismically safe buildings were built.

In this study we use simulation to demonstrate the potential consequences of different emphases in mitigation strategies. Various policy configurations are tested and compared to baseline results. The baseline is established by assuming the continuation of existing policy: building new buildings to the most current building code. Then experiments are carried out to vary the levels of structural mitigation, non-structural mitigation and removing unsafe buildings.

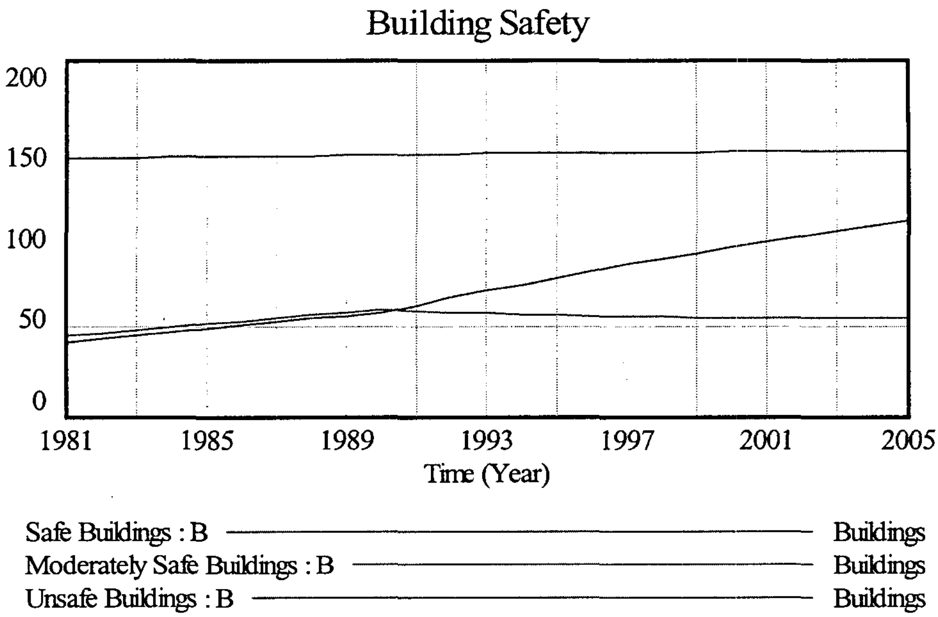
Findings

Since earthquake provisions were not included in building codes until the late 1980s, this community, like most other Mid-western communities in the United States, has a backlog of unsafe building stock. In 1981, the community had 41 (18%) safe buildings, 60 (19%) moderately safe buildings, and 145 (63%) unsafe buildings. By the end of 2005, the community had 110 (35%) safe buildings, 55 (18%) moderately safe buildings, and 149 (47%) unsafe buildings. Table 1 shows the levels by degree of safety for the beginning and end points of the research.

[Table 1] Number and Percentage of safe, moderately safe, and unsafe buildings

	Safe buildings	Moderately safe buildings	Unsafe buildings	Total
1981	41 (18%)	45 (19%)	145 (63%)	231 (100%)
2005	110 (35%)	55 (18%)	149 (47%)	314 (100%)

This baseline trend is reflected in Figure 1.



[Figure 2] Baseline Trend of Building Safety

The policy to build only safe buildings results in sharp increase in the number of safe buildings. Over this 25-year period there were 69 safe buildings, 9 moderately safe buildings, and 4 unsafe buildings added to the community. The disproportional gain in safe buildings improves the community-wide level of safety by increasing the percentage of safe buildings from 18% to 35% and reducing the percentage of unsafe buildings from 63% to 47%.

Impact of Mitigation

Next we explore the impact of mitigation. The policy tested is to build only safe buildings, increase all rates of mitigation, and increase the rate of removing unsafe buildings. Three variations are tested: 2x, 3x, and 4x the rates of structurally and non-structurally mitigating moderately safe and unsafe buildings, and, at the same time, 2x, 3x, and 4x the rate of removing unsafe buildings. The rates of building new buildings are not increased because this would assume community growth beyond the historical pattern. These tests are conducted over the time period of 1981 through 2005 to compare with the baseline data. Table 2 presents results of these increases.

[Table 2] Distribution of Building Safety under Different Policies, As Compared in Year 2005

Rate Increases in Mitigation	Safe Buildings # (%)	Moderately Safe Buildings # (%)	Unsafe Buildings # (%)	Total Buildings # (%)
1x (baseline)	122 (39)	48 (15)	143 (46)	313 (100)
2x	127 (42)	52 (17)	127 (41)	306 (100)
3x	132 (44)	54 (18)	112 (38)	298 (100)
4x	138 (46)	56 (19)	99 (35)	293 (100)

The policy of increasing mitigation and demolishing unsafe buildings results in a community-wide loss of 7 to 20 buildings depending on the magnitude of the mitigation rate increases. Compared to the baseline policy, in year 2005 the increases in mitigation and loss of unsafe buildings policy yields a 3% to 7% gain in the number of safe buildings, a 2% to 4% gain in moderately safe buildings, and a 5% to 11% loss in unsafe buildings. The changes in distribution from the least to most extreme form of this policy show a steady increase in the proportion of both safe and moderately safe, with the gain of safe buildings about twice that of the moderately safe buildings. This is because of the rate of constructing new buildings is higher than the deterioration rate which moves safe buildings into the moderately safe category when they become 20 years old. The relatively small percentage shifts given the huge policy adjustments reveals the stubborn nature of community building distributions. Building safe communities takes time.

Working toward a Safer Future

These results suggest that some adjustment in the community's policy configuration could be desirable. The community has already adopted the policy of constructing only earthquake safe buildings. Over time, this adjustment does improve the distribution of building safety. In 25-years, the proportion of safe buildings will be 8% higher than it is today. Complementing the construction of only safe buildings with a policy of removing unsafe buildings could speed up the process of improving the distribution of building safety. This two-pronged approach would over a 25-year period bring about a nearly equal number of safe and unsafe buildings. The rates of structural mitigation are so small that even 4x the rate showed little improvement. On the other hand, non-structural mitigation appears to be potentially quite useful.

Non-structurally mitigating moderately safe buildings to become safe adds 5% more safe buildings over the practice of building only safe buildings, but does not affect the proportion of unsafe buildings. In contrast, non-structurally mitigating unsafe buildings to become moderately safe has the effect of reducing the proportion of unsafe buildings by 8%, but does not affect the number of safe buildings.

The multi-pronged approach of constructing safe buildings, mitigating, and removing unsafe buildings is the most effective. If adopted, this approach could lead to more than two-thirds of the buildings in the community being safe or moderately safe in the relatively short period of 25 years.

Conclusion

Simulation modeling allows us to see historical patterns and explore the consequences of alternative policies. Our model shows that even though this community began in the late 1980s to build only earthquake safe buildings, the distribution remains skewed in favor of unsafe buildings. The small change over the 25-year period in the number of unsafe buildings shows a practice of retaining old buildings, which are more likely to be unsafe. This practice, plus the fact that buildings are distributed according to the relative amounts of time spent in each respective state (safe, moderately safe, and unsafe), creates a structure that perpetuates the unfavorable distribution of building safety. The baseline ratio of safe to moderately safe to unsafe buildings is about 1:1:2. There are two times as many unsafe buildings as safe ones and also two times the number of unsafe buildings as moderately safe buildings. With the average age of the buildings in this community being about 50 years old it will take an extra emphasis on removing unsafe buildings to counter the built-in tendency governing the current process.

Non-structural mitigation is a useful complement or alternative to removing unsafe buildings. While it would be most beneficial to encourage non-structural mitigation of both unsafe and moderately safe buildings, with limited funds, an emphasis on the unsafe buildings appears to be more effective. Mitigating unsafe buildings would be expected to bring an 8% drop in the proportion of unsafe buildings over a 25-year period.

A limitation of this study is the lack of data on costs associated with the various policies.

The amount of money required to implement a policy is always an important part of the decision-making process. There are good reasons for building owners to keep old buildings, and information about earthquake probabilities is unlikely to convince such owners to replace their buildings.

Since cost is a primary objection to mitigation, more work needs to focus on ways to reduce its cost. More consciously publicizing the tie-in between earthquake and other engineering designs (such as for wind) will help to build and reinforce an awareness and acceptance of earthquake design that does not now exist. Also, as shown in the experiments conducted in this study, shifting the emphasis from structural mitigation to non-structural mitigation is likely to be helpful. A different structure for financial incentives to do mitigation work in new and existing buildings might be in order. Targeting the private sector, specifically insurance companies and associations, may be more effective in encouraging mitigation than getting the government to mandate it. The private sector is seen as having a legitimate right to offer a range of insurance prices, based on the level of protection desired by the consumer. This differs from the government, which creates resentment when it tries to regulate without financial incentives. Policy makers could be focusing efforts toward private enterprise solutions, using local governments as an avenue for technical assistance and education about various mitigation measures. A focus on mitigation makes particularly good sense at this point in time with the government's emphasis on safety.

Finally, on a larger scale, we need to find a way to modify the short term "I don't want to spend my money today" mentality that accompanies this and so many issues today. Our social norms increasingly emphasize the short term, bottom line approach. Perhaps we need to increase our society's sensitivity to the need for a long-range perspective, one that considers the benefits of our actions today to future generations. System dynamics models represent powerful tools for focusing the discussion or behavior over time and exploring possible options.

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Appendix A.
Equations

(01) "average annual # moderately safe buildings built"=
0
Units: Buildings/Year

(02) "average annual # safe buildings built"=
5.38
Units: Buildings/Year

(03) "average annual # unsafe buildings built"=
0
Units: Buildings/Year

(04) becoming moderately safe=
Safe Buildings*fraction safe deterioration
Units: Buildings/Year

(05) becoming unsafe=
Moderately Safe Buildings*fraction moderately safe deteriorating
Units: Buildings/Year

(06) building moderately safe buildings=
"average annual # moderately safe buildings built"
Units: Buildings/Year

(07) building safe buildings=
"average annual # safe buildings built"
Units: Buildings/Year

(08) building unsafe buildings=
"average annual # unsafe buildings built"
Units: Buildings/Year

(09) FINAL TIME = 2005
Units: Year
The final time for the simulation.

(10) fraction mitigating structurally=
0.0003
Units: 1/Year

(11) fraction moderately safe deteriorating=

0.0175

Units: 1/Year

(12) fraction ms razed=

0.013

Units: 1/Year

(13) fraction ns mitigating ms to s=

0.005

Units: 1/Year

(14) fraction ns mitigating us to ms=

0.0035

Units: 1/Year

(15) fraction safe deterioration=

0.014

Units: 1/Year

(16) fraction safe razed=

0.013

Units: 1/Year

(17) fraction us razed=

0.002

Units: 1/Year

(18) INITIAL TIME = 1981

Units: Year

The initial time for the simulation.

(19) losing moderately safe buildings=

Moderately Safe Buildings*fraction ms razed

Units: Buildings/Year

(20) losing safe buildings=

Safe Buildings*fraction safe razed

Units: Buildings/Year

(21) losing unsafe buildings=

Unsafe Buildings*fraction us razed

Units: Buildings/Year

(22) Moderately Safe Buildings= INTEG (

becoming moderately safe+building moderately safe buildings+"non-structural mitigating"

-becoming unsafe-losing moderately safe buildings-"non-structural mitigating ms", 45)

Units: Buildings

(23) "non-structural mitigating"=

Unsafe Buildings*fraction ns mitigating us to ms

Units: Buildings/Year

(24) "non-structural mitigating ms"=

Moderately Safe Buildings*fraction ns mitigating ms to s

Units: Buildings/Year

(25) Safe Buildings= INTEG (

+building safe buildings+"non-structural mitigating ms"+structural mitigating -becoming moderately safe-losing safe buildings,

41)

Units: Buildings

(26) SAVEPER =

TIME STEP

Units: Year [0,?]

The frequency with which output is stored.

(27) structural mitigating=

Unsafe Buildings*fraction mitigating structurally

Units: Buildings/Year

(28) TIME STEP = 1

Units: Year [0,?]

The time step for the simulation.

(29) Unsafe Buildings= INTEG (

becoming unsafe+building unsafe buildings-losing unsafe buildings-"non-structural mitigating"

-structural mitigating,

145)

Units: Buildings

논문접수일: 2005.12.16 / 심사완료일: 2006.03.10