Health Disturbance of Residents in Houses Tilted Due to Liquefaction during the Great East Japan Earthquake

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SUMMARY:
The 2011 off the Pacific coast of Tohoku Earthquake triggered liquefaction of soil in wide areas of Japan. In particular, a number of damaged houses were found in the land reclamation areas of the Kanto region. Some residents who lived in houses that were tilted by liquefaction complained of health disorders. We report on the results of a questionnaire survey of residents in Mihama Ward, Chiba City, about the characteristics of their houses, earthquake damage, health disturbances, and so on. Probability models of health disturbance with respect to house tilt angle due to liquefaction are constructed based on the survey data. The probability that a respondent experienced health disturbance was found to be considerably higher when the tilt angle exceeded 0.013 rad.

Keywords: Liquefaction, Great East Japan Earthquake, Health disturbance, Detached house

1. INTRODUCTION

During the 2011 Great East Japan Earthquake, soil liquefaction was widespread in many areas. In particular, many liquefaction-damaged detached houses were situated on reclaimed land in the Kanto region. A number of residents complained of health disturbances due to their houses being subjected to large tilting.

Health disturbances that result from inhabiting a building tilted by liquefaction have been studied by several researchers. Kitahara and Uno (1965) investigated the effect on residents and workers of buildings tilted by the Niigata earthquake of June 16, 1964. On the basis of interviews conducted in November 1964, they discussed the causes of conditions such as vertigo. Uno and Endo (1996) conducted a study on 42 female residents who lived in an accommodation unit tilted by the 1964 Niigata earthquake by interviewing the residents in 1981. They also carried out experiments using equipment that simulated a tilted building; specifically, examinees were led into a sloped room and their perception was analyzed when taking an ordered posture: sitting on the floor, taking a chair, lying on their back, and walking in the room (Endo and Uno 1981, Uno and Endo 1996). Additionally, Endo and Uno (1982) analyzed the perception of examinees when looking through a tilted window frame.

Fujii et al. (1998) surveyed around 100 houses in Ashiya City that were damaged by liquefaction during the 1995 Hyogo-ken Nanbu Earthquake. As a consequence, they established a relation between a building's tilt angle and its functional failure. Yasuda and Hashimoto (2002) and Yasuda (2004) also surveyed a liquefaction-damaged housing estate in Abe-Hikona, Yonago City, which was struck by the 2000 Western Tottori Prefecture Earthquake. Accordingly, Yasuda and Hashimoto inferred that a house tilt angle of 1/100 rad was the bearable limit for a resident, and that leveling repair was required for houses on slopes larger than this because of health disturbances.

To reveal liquefaction-induced health disturbances resulting from the 2011 Great East Japan Earthquake, we conducted a questionnaire survey during consultation meetings with residents held at Mihama Ward Office, Chiba City. The aim of the meetings was to repair the detached houses damaged by liquefaction. Participants at the meeting were asked about the characteristics of their residences, seismic damage, health disturbances, and so on. On the basis of this survey data, we present probability models of heath disturbance occurrence with respect to house tilt angle due to liquefaction.

2. QUESTIONNAIRE SURVEY

2.1. Outline of questionnaire survey

This questionnaire survey was carried out during four sessions of meetings at Mihama Ward Office, Chiba City. On August 20, 21, 27, and 28, 2011, we interviewed 26, 12, 17, and 13 households, respectively. Thus, a total of 68 households gave responses to the survey. However, one household did not suffer liquefaction damage, and so the target of our analysis is 67 households composed of 80 residents (42 men and 38 women). Note that all householders were owner-occupiers.

2.2. Specification of houses

Fig. 2.1 shows the structural types of houses covered in the survey; 41 (61%) houses were built of timber frameworks and 8 (19%) of light-gauge steel. Observing the construction years in Fig. 2.2, the number of relatively new houses—which had replaced old houses due to deterioration with age or change of owner—was moderately large. In 1981, the Building Standard Law of Japan considerably increased the earthquake resistance requirements of new buildings; however, 22% of houses in the survey were constructed from 1971 to 1980, and therefore conformed to the old earthquake resistance standards. We also note here that 24 houses (36%) were renovated or enlarged by their owners after construction.

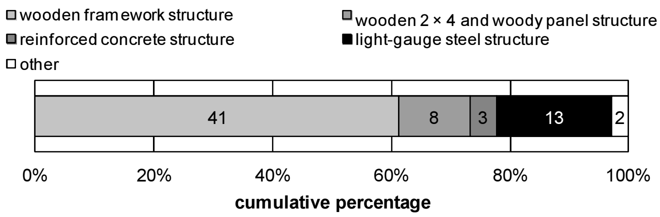

Figure 2.1. Structural types of houses ($N = 67$)

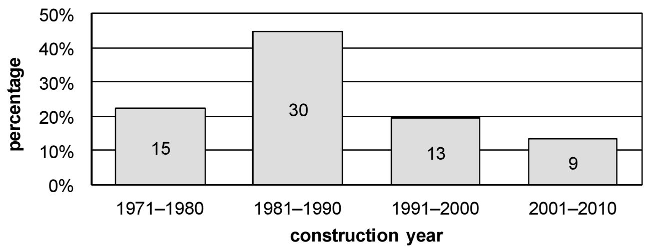

Figure 2.2. Construction years ($N = 67$)

Sixty-six of the houses had two stories, and one had three stories. Regarding their use, 66 of the houses were used exclusively as residential dwellings, whereas the final one was used as both a dwelling and an office. Among the 67 houses, 36 (54%) were ready-built and 31 (46%) were custom-built.

A considerable number, 47 (70%), of the houses were built on footing foundations, and 12 others (18%) on mat foundations (Fig. 2.3). From Fig. 2.4, three houses (4%) had soil reinforcement and 23 (34%) of the households had conducted subsurface exploration. Breaking down the houses by construction year, a high percentage of respondents conducted subsurface exploration if their house was built after 2001 (Fig. 2.5).

Fig. 2.6 shows that 65 (97%) and 46 (69%) of households were not given any information on liquefaction and earthquake resistance, respectively. However, respondents living in newly built houses were more likely to have received information on earthquake resistance (Fig. 2.7).

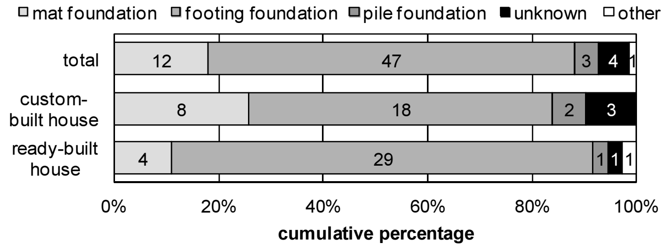

Figure 2.3. Foundation types ($N = 67$)

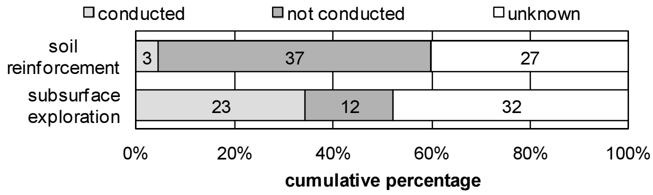

Figure 2.4. Soil reinforcement and subsurface exploration ($N = 67$)

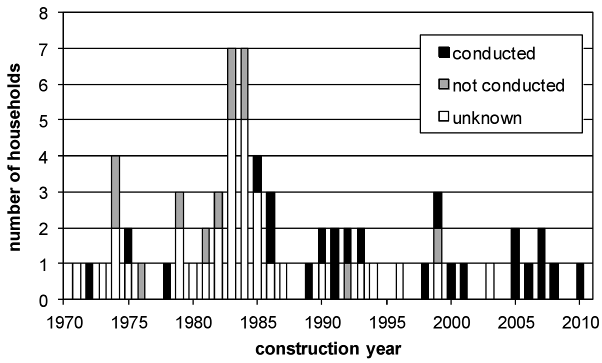

Figure 2.5. Number of households conducting subsurface exploration by house construction year ($N = 67$)

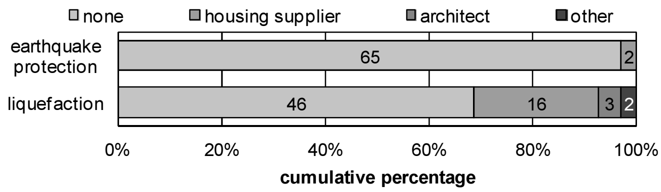

Figure 2.6. Disseminator of information on liquefaction and earthquake resistance ($N = 67$)

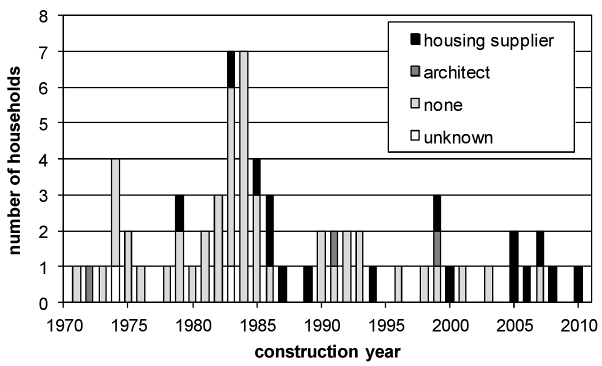

Figure 2.7. Disseminator of information on earthquake resistance by house construction year ($N = 67$)

2.3. Seismic damage

Seismic damage to the respondents' houses is now discussed. Fig. 2.8 shows the damage certificates issued by the local government in Chiba City. Thirty-seven (55%) of the houses were judged to have been partially destroyed, whereas none of the respondents' houses were deemed to be completely destroyed. The damage as evaluated by insurance companies is shown in Fig 2.9. Only 37 (55%) households had earthquake insurance policies, and of these, 22 were judged to have half loss (20% ≤ loss ratio < 50%), 10 to have total loss (50% ≤ loss ratio), and the remainder to have partial loss (3% ≤ loss ratio < 20%).

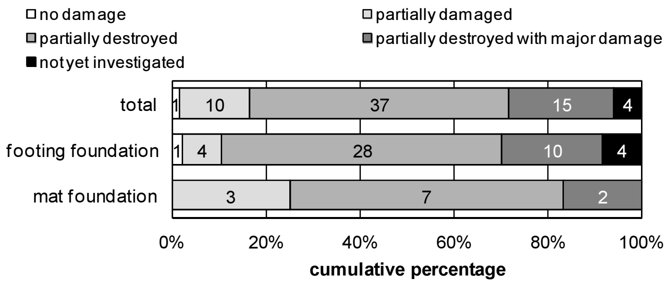

Figure 2.8. Damage certificates issued by local government ($N = 67$)

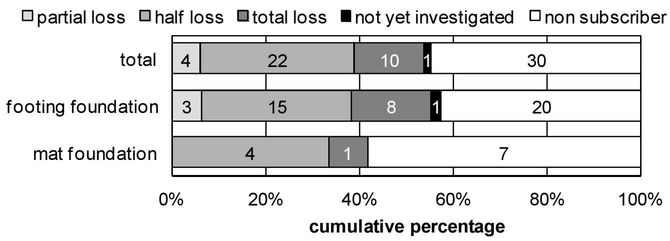

Figure 2.9. Damage level according to earthquake insurance companies ($N = 67$)

Next, the damage situation is described. Fig. 2.10 shows the ground damage at the sites of the houses. Sand boils occurred at 64% of the housing lots. The occurrence of cracks in foundations and outer walls of the houses are shown in Fig 2.11. Comparatively more cracks were found in foundations than in the outer walls.

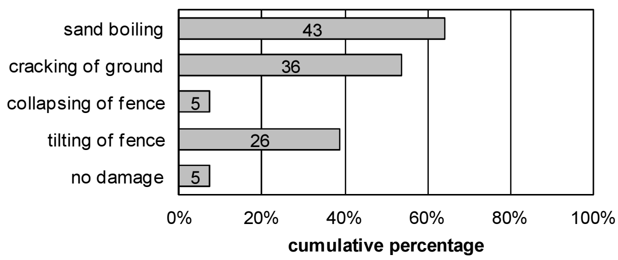

Figure 2.10. Damage to housing lots ($N = 67$)

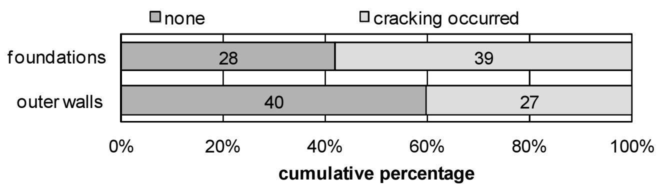

Figure 2.11. Cracks in foundations and outer walls ($N = 67$)

Fig. 2.12 shows the relation between the house tilt angle measured by the local government when issuing damage certificates and the construction year. During measurements, an inspector uses a plumb-bob suspended from a 120-cm-long string to determine the tilt angles of the columns or walls at all four corners of a house. The average of these four measured values is used to categorize the level of damage (indicated on the right-hand axis of Fig. 2.12).

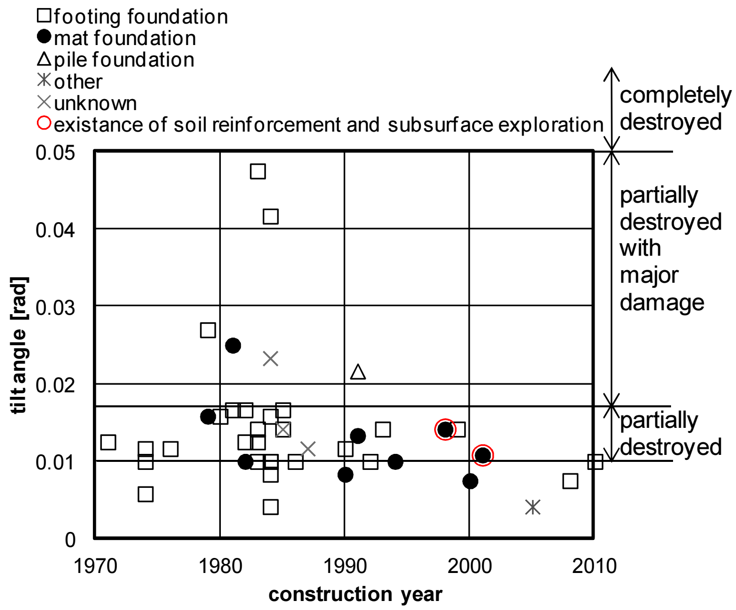

Figure 2.12. Relation between house tilt angle and construction year (N = 43 respondents provided tilt angle data surveyed by local government)

A tilt angle criterion for "completely destroyed" (tilt angle ≥ 1/20 rad) had already been set before the disaster. To save the disaster victims suffering from the widespread liquefaction damage to houses that occurred during the Great East Japan Earthquake, house tilt angles related to the following two damage categories were additionally set:

- Partially destroyed with major damage: 1/60 ≤ tilt angle < 1/20 rad.
- Partially destroyed: 1/100 rad ≤ tilt angle < 1/60 rad.

According to Fig. 2.12, mat foundations were often adopted in newly built houses. However, houses with tilt angle exceeding 1/60 (≈0.017) rad tended to have footing foundations, whereas all houses with mat foundations had tilt angles of <1/60 rad.

Finally, 85% of the households claimed that they had been inconvenienced by a door moving automatically due to tilt of their house (Fig. 2.13).

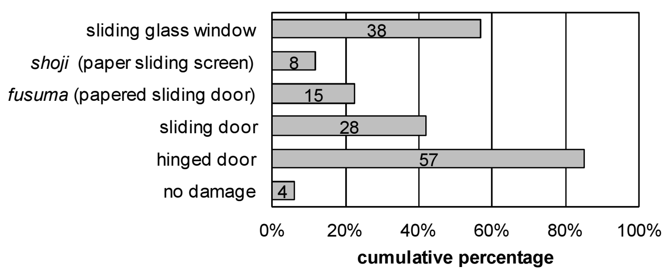

Figure 2.13. Damage to door fittings (N = 67)

2.4. Health disturbances

In this section, health disturbances of the respondents are discussed. First, breaking down the respondents by age and gender in Fig 2.14, we see that a high percentage of residents are in their 60s or above, especially women.

Fig. 2.15 shows the residents' sensitivity to tilting. Among the 80 respondents, 55 (men: 27; women: 28) were clearly aware of the tilting of their houses. The percentage of women who strongly felt this tilting was larger than that of men. A possible explanation is that spending long periods at home or doing housework might make them feel the tilt strongly.

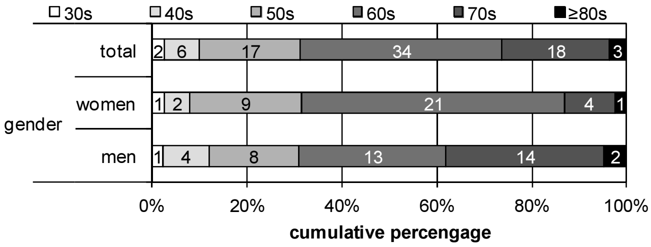

Figure 2.14. Age and gender of respondents ($N = 80$)

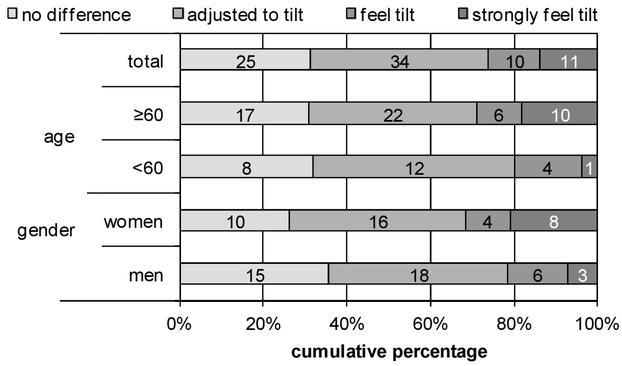

Figure 2.15. Sensitivity to house tilt at the time of the survey ($N = 80$)

A clear correlation cannot be seen between resident tilt adjustment time and the house tilt angle measured by the local government (Fig. 2.16); the adjustment time seems to differ from one case to another. A number of tilt-related symptoms were experienced by residents between the occurrence of the Great East Japan Earthquake and the present survey (some of which are shown in Fig. 2.17). Some complained of shoulder stiffness, foot pain, and other health disturbances, while others respondents stated that existing disorders became worse after the earthquake. Note that the causes of these health disturbances might be related not only to the slope of the floor but also to the vibration of the aftershocks.

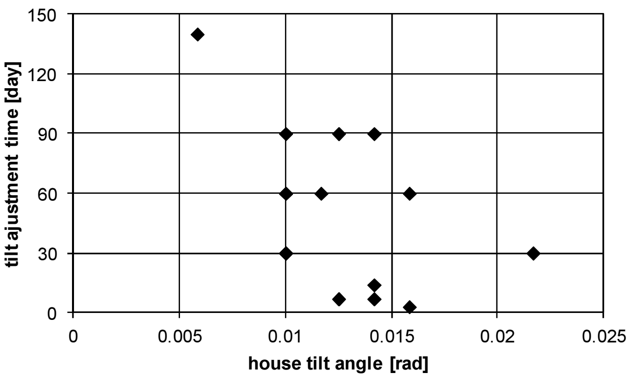

Figure 2.16. Relation between tilt adjustment time and house tilt angle ($N = 15$ respondents provided both tilt angle as surveyed by local government and their time to adjust to tilt)

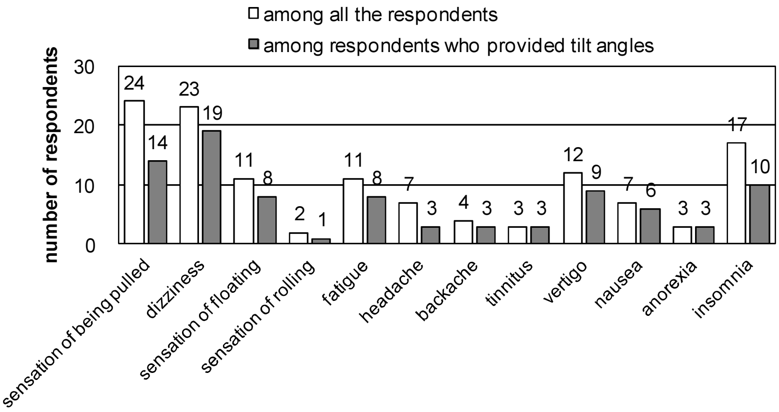

Figure 2.17. Tilt-related symptoms between occurrence of the earthquake and present survey (N = 80 respondents in total and N = 54 respondents provided tilt angles)

Fig. 2.18 shows the changes in health condition between the earthquake's occurrence and the present survey of the 55 respondents who were aware of their house's tilt. A relation between a resident's change in health and age or gender is not obvious from these findings.

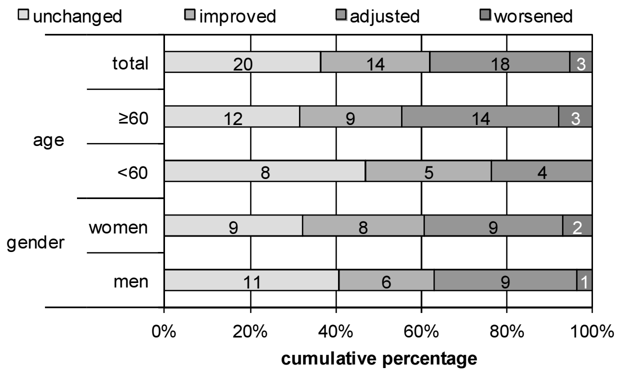

Figure 2.18. Evolution of health state between occurrence of the earthquake and present survey (N = 55 respondents were aware of their house's tilt)

A number of householders experienced vertigo when leaving their house; female respondents aged 60 or over were particularly troubled by this condition (Fig. 2.19). Some respondents complained that their symptoms worsened when they observed tilted utility poles or buildings. Several residents who had become accustomed to the tilting of their house felt that the outside world was somehow leaning.

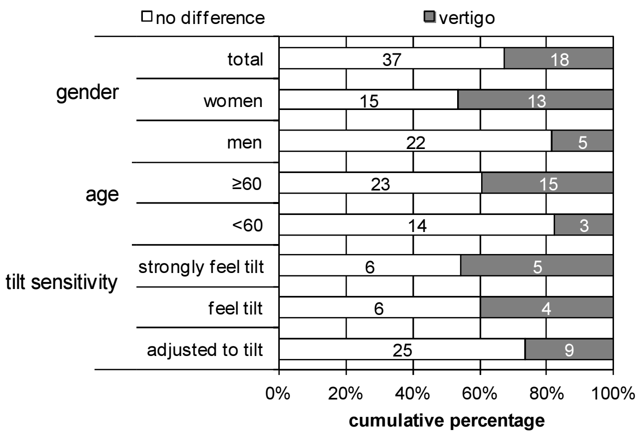

Figure 2.19. Experiencing vertigo when leaving house (N = 55 respondents were aware of their house's tilt)

3. HEALTH DISTURBANCE MODEL

Logarithmic probit models (log-normal models) of health disturbances are constructed with respect to house tilt angle due to liquefaction. Questionnaire data of the 54 respondents in the 43 houses that provided tilt angles measured by the local government are available for constructing these models. Although several respondents provided tilt angles measured by other institutions, such as insurance companies and builders, we used only the abovementioned angles to avoid mixing data determined by different measurement methods.

The symptoms in Fig 2.17 are aggregated into two categories. “sensation of rolling”, “sensation of floating”, “dizziness”, and “vertigo” are amalgamated into a *vertigo* category. All other symptoms in Fig. 2.17, except for “sensation of being pulled” are amalgamated into a *health disturbance* category. From Fig. 2.18, the majority of the respondents are aged 60 or over. Since health disturbances often occur due to aging, we divide the survey data into age groups and examine the relation between these groups and house tilt angle. A scatter plot of this relation and the associated regression line are shown in Fig. 3.1. Since we employ log-normal models, the natural logarithm of the tilt angle is plotted along the x-axis. The coefficient of determination $R^2 = 0.1019$ and therefore little correlation is found between the parameters.

A maximum likelihood method is employed to construct the log-normal models, and the parameters of the resulting models are listed in Table 3.1. Figs. 3.2 and 3.3 present the vertigo and health disturbance models, respectively. The points on the respective 0% and 100% lines in the plots denote the survey data regarding the absence or presence of each symptom. The probability of experiencing vertigo increases rapidly when the tilt angle exceeds 0.0159 (= 1/62.8) rad. Similarly, the probability of experiencing health disturbances increases sharply at angles greater than 0.0128 (= 1/77.9) rad. These tilt angles correspond to the medians of the two distributions. The majority of the data in the present survey concern relatively small tilt angles compared with Kitahara and Uno (1965) and Uno and Endo (1996), and it is notable that the current model reveals the tilt threshold for health disturbances.

Figure 3.1. Relation between house tilt angle and respondent age group

Table 3.1. Parameters values of health disturbance models

Symptom	Logarithmic mean	Median [rad]	Logarithmic standard deviation
vertigo	−4.14	0.0159 (= 1/62.8)	0.997
health disturbance	−4.36	0.0128 (= 1/77.9)	0.842

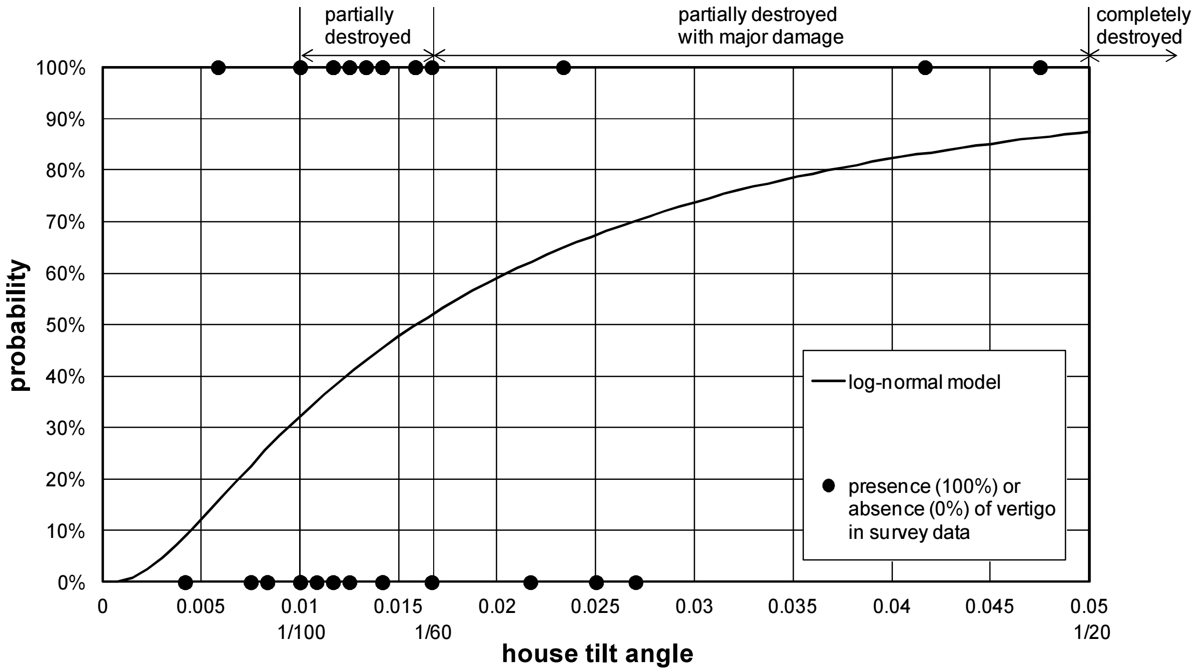

Figure 3.2. Probability model of vertigo occurrence with respect to house tilt angle

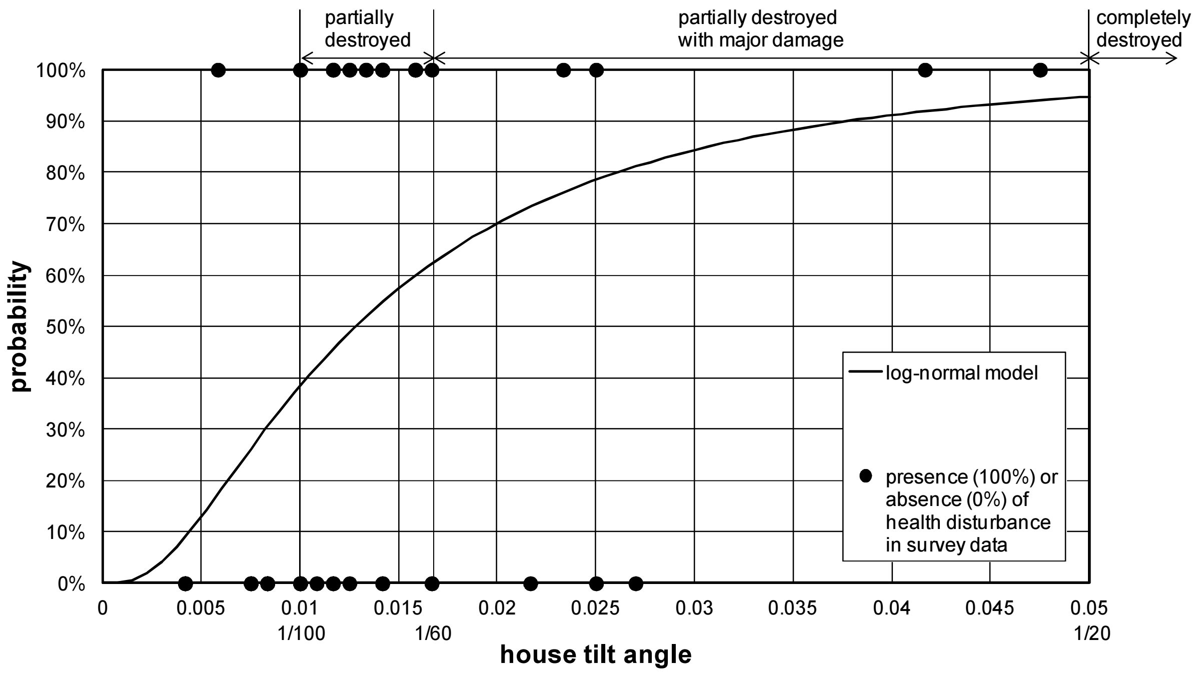

Figure 3.3. Probability model of health disturbance occurrence with respect to house tilt angle

4. CONCLUSIONS

A questionnaire survey was conducted by interviewing residents of Mihama Ward, Chiba City, whose houses were damaged by liquefaction during the 2011 Great East Japan Earthquake. On the basis of data collected on 54 respondents who provided house tilt angles measured by the local government to issue damage certificates, logarithmic probit models of health disturbances were constructed with respect to tilt angles. The statistical models suggest that tilt angles exceeding approximately 0.013 rad can cause health disturbances. However, since the standard deviations in the models are not negligible, even if tilt angles are smaller than 1/100 rad, all households must be conscientiously investigated to prevent health inconveniences to residents.

Our challenge for the future is to improve the reliability of the current probability model such that its results can be applied with confidence. In addition, since Kitahara and Uno (1965) reported a very limited number of infant cases, the age of respondents in Uno and Endo (1996) are women between the ages of 18 and 27, and those in the present survey are men and women aged 30 or over, a survey of the younger segment of society (i.e. <17 years, and more particularly young children) is expected.

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REFERENCES

Endo, Y. and Uno, H. (1981). "A Study on the Sense of Equilibrium of Man: The Case of Sloping Floor." *Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan*, Vol. Architecture and Planning, 1237-1238. (in Japanese)

Endo, Y. and Uno, H. (1982). "A Study on the Sense of Equilibrium of Man: The Case of Sloping Window Frame." *Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan*, Vol. Architecture and Planning, 1465-1466. (in Japanese)

Fujii, M., Ijuin, H., Tamura, M., and Ina, K. (1998). "Damage and Restoration of Foundation for Houses in Liquefied Areas by the Hyogo-ken Nanbu Earthquake: Concept for Restoration of Foundation for Houses." *Soil Mechanics and Foundation Engineering*, **46:7**, 9-12. (in Japanese)

Kitahara, M. and Uno, R. (1965). "Dizziness and Balance in the Sloping Room: Survey of Buildings Tilted by the Niigata Earthquake." (title translated by the authors) *Practica oto-rhino-laryngologica*, **58:3**, 145-151. (in Japanese)

Uno, H. and Endo, Y. (1996). "A Study on the Sense of Equilibrium of Man: The Threshold Value of the Sense of Equilibrium on Sloping Floors." *Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ)*, **No. 490**, 119-125. (in Japanese)

Yasuda, S. and Hashimoto, T. (2002). "Liquefaction-Induced Settlements of Houses During the Western Tottori Prefecture Earthquake." (title translated by the authors) *Proceedings of the 57th Annual Conference of the Japan Society of Civil Engineers*, 1029-1030. (in Japanese)

Yasuda, S. (2004). "Damage of Housing Estate Due to the Western Tottori Prefecture Earthquake." (title translated by the authors) *Sougou-Ronbun-Shi (New Frontiers in Architecture for Damage Mitigation and Recovery from Disasters)*, Architectural Institute of Japan, **2**, 45-46. (in Japanese)