A spatially-correlated tsunami evacuation destination choice model：A case study of the Great East Japan Earthquake.
空間相関に着もした気仙沼における避難目的選択モデル

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This article focuses on the estimation of a tsunami evacuation destination choice accounting for spatial correlation among alternatives via a Spatially Correlated Logit (SCL). Spatial aggregation of alternatives is conducted using a safety(risk) indicator as a function of altitude and expected tsunami wave height. Findings suggest a marginal improvement of the SCL model as compared to the traditional Multinomial Logit Model (MNL). In addition a new allocation parameter is suggested in order to account for risk correlation among alternatives.

Key Words : *evacuation behavior, destination choice, spatial correlation, tsunami*

1. BACKGROUND

An understanding of the mechanisms behind evacuation travel behavior during emergency situations is very important to support evuacation planning and disaster prevention measures. In emergency situations, the evacuation process can be divided into three main steps. (i) evacuation participation and departure time choice, (ii) destination choice and (iii) route choice (Pel 2012). In this respect, in the evacuation related literature the destination choice issue is a rather under-studied aspect when compared to other facets of the process. This is one of the main motivations of this analysis.

From a dissagreate perspective, most studies have relied on discrete choice theory, either by estimating (i) evacuation destination type such as public shelters, relatives or fiends, and others (Whitehead et al. 2000, Brodie et al. 2006, Cuellar et al. 2009), or by directly modeling spatial location choice (Cheng & Wilmot 2009)). In addition, most studies in the literature have focused disasters such as hurricanes, which allow to a large extent the time to make a rather informed decision on wether to evacuate or not, and if so, where to. On the other hand, in events such as tsunamis, decisions have to be made in a quick manner and under a lot of uncertainty.

3. DATA CHARACTERISTICS

Data from a survey on evacuation behavior conducted by the Ministry of Land Infrastructure, Transport and Tourism (MLIT) was used. The survey was conducted on survivors of the Great Eastern Japan Eartquake and ensuing tsunami. A total of 10,603 valid samples were gathered from 63 cities and towns in 6 prefectures. The present study used data from Kesennuma City, in Miyagi Prefecture. As of March 2015, the city of Kesennuma reports 1358 deaths, 222 missing persons, and 9,500 displaced (Kesennuma City 2015). The Japanese Meteorological Agency also reported maximum floods of over 19 meters. (JMA 2011).

As a preliminary study, the city center area was selected as target area, as illustrated in Figure 1. The effective sample size was 481.

In terms of evacuation timing, as illustrated in figure 2, at the time of arrival of the first tsunami leading wave (approximately 20 minutes after the earthquake), only around 40% of the respondents had evacuated. Even one hour after the earthquake, only 70% of the respondents had evacuated.

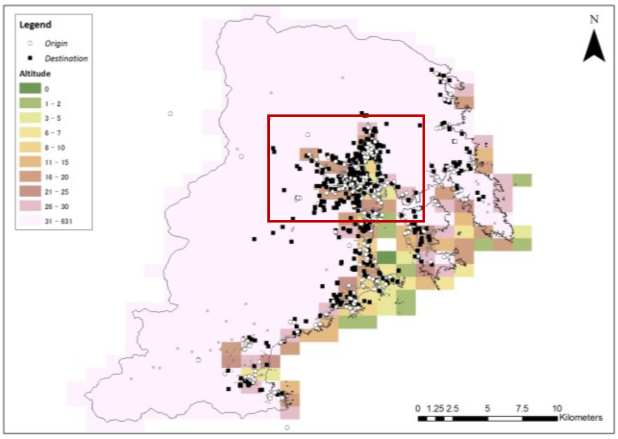

Figure 1. Evacuation OD in and study area

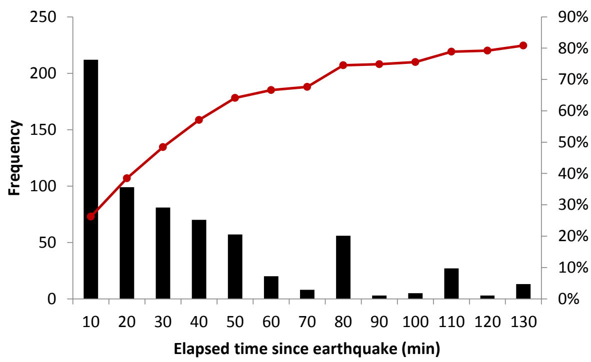

Figure 2. Distribution of evacuation times

3. MODEL CHARACTERISTICS

The multinomial logit model is the workhorse of discrete choice theory due to the elegant closed form of its probability function. A limitation however, is the Independence of Irrelevant Alternatives property (IIA) which does not allow for correlation among alternatives. In the case of spatial choices, the property is particularly relevant to spatial correlation issue. Several extensions of the MNL have been proposed to allow for correlation among alternatives such as the Spatially Correlated Logit (SCL) (Bhat and Guo 2004), the Generalied Nested Logit (GNL) (Wen and Koppelman 2001) or the Cross-Nested Logit (CNL) (Bierlaire 2006) among others.

The SCL model proposed by Bhat and Guo (2004) was explicitly constructed to account for spatial correlation in destination choice modeling. The probability of choosing alternative i is given by

$$P(i) = \sum_{j \neq i} \frac{\alpha_{i,ij} \exp(V_i)^{1/\rho}}{\left(\alpha_{i,ij} \exp(V_i)^{\frac{1}{\rho}}\right) + \left(\alpha_{j,ij} \exp(V_i)^{\frac{1}{\rho}}\right)} \times$$

$$\frac{\left[\left(\alpha_{i,ij} \exp(V_i)^{\frac{1}{\rho}}\right) + \left(\alpha_{j,ij} \exp(V_i)^{\frac{1}{\rho}}\right)\right]^{\rho}}{\sum_{k=1}^{I-1} \sum_{l=i+1}^{I} \left(\alpha_{k,kl} \exp(V_i)^{\frac{1}{\rho}}\right) + \left(\alpha_{l.kl} \exp(V_i)^{\frac{1}{\rho}}\right)}$$

where $\alpha_{i,ij} = \frac{A_{ij}}{\sum_j A_{ij}}$ is an allocation parameter defined on adjacency. A_{ij} takes value "1" if zones i and j are adjacent and zero otherwise. Bekhor and Prashker (2008) adapted the allocation parameter to make it a function of common length of adjacent zones, such that $\alpha_{i,ij} = \frac{L_{ij}}{\sum_j L_{ij}}$, where L_{ij} is the length of the common boundary of zone par ij.

As mentioned, earlier, as a preliminary study, the target area is limited to the city center area. Spatial aggregation was done based on risk level, as a function of location altitude. Although in theory, if tsunami height information was 100% accurate, a safety threshold could be easily drawn. However, since there is a lot of uncertainty in the wave height estimate, this threshold is uncertain. Hence we propose a safety perception indicator (risk level) based on available information at the moment (i.e. reported wave height during evacuation advisory). As illustrated in Figure 3, to account for the uncertainty in this estimate, the safety percetion indicator S(h) can be conceptualized as a truncated logistic curve, where every value below the safety threshold (estimated tsunami height) has a value of 0, and S(h) gradually increases as altitude increases, with diminishing gains as locations get higher and higher.

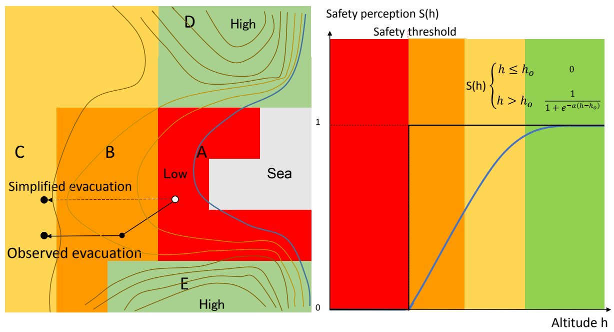

Figure 3. Spatial aggregation based on risk level

Based on this concept, the target area was aggregated into 8 large zones as illustrated in Figure 4.

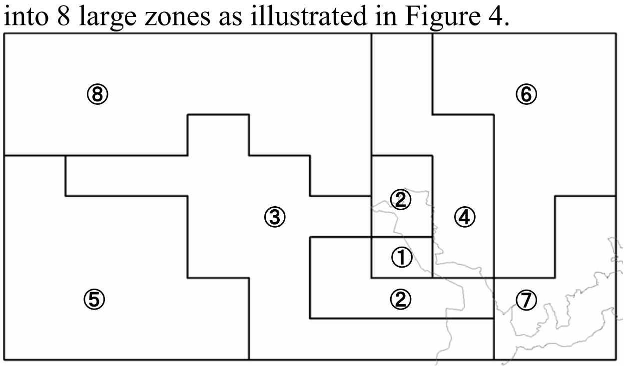

Figure 4. spatial aggregation of alternatives

4. ESTIMATION RESULTS

For comparison purposes three models were estimated, the traditional MNL model to serve as a reference. An SCL model with an adjacency-based allocation parameter, and and SCL with an common-length based allocation parameter. Results are summarized in Table 1.

Table 1. Model estimation results

	MNL			SCL1 (Adjacency only)			SCL2 (Adjacent Distance)		
Parameter name	**Coefficient**	**S..E.**	**t-stat**	**Coefficient**	**S..E.**	**t-stat**	**Coefficient**	**S..E.**	**t-stat**
City center dummy (Zones 1 and 2)	20.70	19.66	1.05	20.41	115.69	0.18	21.81	249.44	0.09
Log of OD distance*Car	-0.22	0.04	-5.92	-0.19	0.02	-7.71	-0.16	0.05	-3.44
Log of OD distance*Other	-0.38	0.04	-8.94	-0.23	0.03	-8.54	-0.27	0.07	-3.74
Log of OD altitude difference	5.13	0.41	12.65	3.87	0.36	10.72	3.93	0.70	5.62
Log of OD altitude difference^2	-0.53	0.09	-5.82	-0.36	0.05	-7.52	-0.34	0.11	-2.96
Average slope	-1.17	0.11	-10.83	-1.01	0.09	-11.82	-1.01	0.13	-7.88
Size variable: Log of number of buildings	1.07	0.14	7.84	0.50	0.04	11.42	0.76	0.19	4.01
Scale parameter	1.00	-	-	0.08	0.03	2.70	0.51	0.22	2.30
LL(0)	-1000.20			-1000.20			-1000.20		
LL(β)	-312.32			-302.4347			-310.86		
ρ^2	0.6877			0.6976			0.6892		
adjusted ρ^2	0.6807			0.6896			0.6812		

In general, all three models performed wll with estimated psedo-rho square well above 0.60. In terms of parameter estimates, as expected the OD distance had a negative effect on destination choice location, with different magnitudes for car users and non-car users. The OD altitude difference was specficied as a quadratic function. Coefficient signs suggest that the OD difference in altitude has a positive utility at first but after a certain threshold the utility becomes negative. This is intuitive as people will try to evacuate to high lands as much as possible but very high places are unaccessible due to poor accessibility and steep slopes. The sign on the slope coefficient. reinforces this hypothesis. From a theoretical standpoint, the size variable is within range for both SCL models, and just slightly over 1 in the MNL model.

In terms of differences among models, goodness of fit of all models are very similar, suggesting if anything, that the improvements of incorporating spatial correlation into the analysis might be marginal, or spatial correlation might not be adequately captured with the existing approaches.

5. DISCUSSION AND CONCLUSION

This article focused on the estimation of a tsunami evacuation destination choice model accounting for spatial correlation. Although results suggest some marginal improvements to the traditional MNL model, we would like to point out instead, several avenues for deepening our understanding of the issue at hand. First of all, the choices in the present study were limited to the central area of the city for simplicity purposes. Further steps involve expanding the analysis area to the totality of the city jurisdisction. Secondly, although the concept of spatial aggregation based on risk levels is appealing, if risk is a function of altitude, then spatial aggregation will emulate topographical features of the area and will result in unorthodox aggregation schemes, which might cause some problem when estimating spatial reference variables such as distance. It also might make the analysis particularly sensitive to the Modifiable Areal Unit Problem, which might have unpredictable effects in estimation results (Fotheringham & Wong, 1991).

A particular alternative to this problem could be to incorporate risk levels in the allocation parameter itself and do without the risk-based aggregation scheme. A possible allocation parameter estimator can be:

$$\alpha_{i,ij} = \left(\frac{A_{ij}}{2\sum_j A_{ij}}\right) + \left(\frac{R_{ij}}{2\sum_j R_{ij}}\right)$$

where as before, A_{ij} takes value 1 when zones i and j are adjacent, and zero otherwise. Similarly, R_{ij} is a risk indicator (i.e. altitude) that takes value 1 when the adjacent zone has the similar risk levels. This similarity can be estimated either by classifying risk by levels, or using a smoothing parameter.

This is illustrated in Figure 5, where risk is identified by color, hence same colors roughly mean same risk level. The numbers in blue illustrate the allocation parameter value of the central unit in reference to the adjacent units. Compared to the adjacency only case, the adjacency and risk-based allocation parameters weight higher those units within the same risk range.

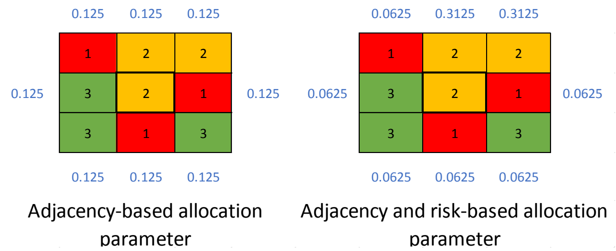

Figure 5. Allocation parameter comparison

Finally, since evacuation decisions are likely codependent on other factors such as evacuation timing, future research should focus on joint estimation, in order to account for these interaction.

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