PIPELINE DAMAGE ASSESSMENT THROUGH MONTE CARLO SIMULATION

by

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ABSTRACT

PIPELINE DAMAGE ASSESSMENT THROUGH MONTE CARLO SIMULATION

Earthquakes are one of the most catastrophic events among all the disasters. They affect societies in many aspects including life losses and economic losses. Besides the life losses, a lot of people get injured and become disabled due to earthquakes. As being parts of the lifeline systems in a city, potable water systems, wastewater systems, electricity systems, etc. are vital for human life. The impediments in the serviceability of these lifeline systems, put people's lives in danger even after an earthquake. Studies to reduce the negative effects of earthquakes and guess the serviceability of a lifeline system after an earthquake has gained major importance.

In this study, algorithms to predict the number of damages on the water pipeline system due to an earthquake suggested by both HAZUS-FEMA (2003) and the American Lifeline Alliance (ALA-2001) are compared. Moreover, the Monte Carlo simulation technique is introduced to these two methods and the results of these methods through Monte Carlo simulation are also compared. To perform the analyses, a generic study of the Zeytinburnu potable water system in Istanbul is examined with four different pipe material types, namely, concrete, bellmouth concrete, steel, and polyethylene under a scenario earthquake generated by ELER software. Concrete and steel pipes have large diameters, whereas bellmouth concrete and polyethylene pipes have small diameters in this study. With these different pipe material types, the effects of being brittle and being ductile materials on pipe failures are also evaluated and compared.

ÖZET

BORU HATLARI HASARLARININ MONTE CARLO SİMÜLASYONU İLE DEĞERLENDİRİLMESİ

Depremler, tüm doğal afetler arasında en fazla yıkıcı etkiye sahip olan ve toplumları can kayıplarından ekonomik kayıplara kadar bir çok yönden etkileyen felaketlerdir. Can kayıplarının yanı sıra, depremler sonucunda bir çok insan yaralanmakta veya engelli hale gelebilmektedirler. İçme suyu sistemleri, atık su sistemleri, elektrik sistemleri vb. bir şehirdeki yaşam hatları olarak, insan yaşamı için hayati önem taşımaktadırlar ve bu yaşam hatlarının servisinde meydaha gelecek herhangi bir gecikme, depremden sonra bile olsa insanların yaşamlarını tehlikeye atmaktadır. Bu nedenle, depremlerin olumsuz etkilerini azaltmak ve deprem sonrası yaşam hatlarının servis edilebilirliğini tahmin edebilmek büyük önem kazanmıştır

Bu çalışmada, HAZUS-FEMA (2003) ile American Lifeline Alliance (ALA-2001) tarafından önerilen ve deprem sonrası içme suyu boru hatlarında oluşabilecek hasar sayılarını tahmin etmekte kullanılan yöntemler kıyaslanmaktadır. Ayrıca, bu iki yönteme Monte Carlo simulasyonu uygulanarak elde edilen sonuçlar karşılaştırılmaktadır. Bu çalışmayı gerçekleştirmek için, İstanbul'un Zeytinburnu ilçesinde bulunan içme suyu boru hatlarıyla, jenerik bir çalışma yapılmıştır. Bu çalışmada, ELER tarafından üretilen senaryo depremi kullanılmıştır. Bu çalışma kapsamında geniş çaplı betonarme boru, küçük çaplı muflu beton boru, geniş çaplı çelik boru ve küçük çaplı polietilen borular kullanılarak gevrek ve sünek boru malzemelerinin deprem kaynaklı boru hasarına etkisi değerlendirilmektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

e	Euler's number, 2.71828

LIST OF ACRONYMS/ABBREVIATIONS

AC	Asbestos cement
ALA	American Lifeline Alliance
ASCE	American society of civil engineers
CI	Cast Iron
ELER	Earthquake Loss Estimation Routine software
FEMA	Federal Emergency Management Agency
GMPE	Ground Motion Prediction Equation
HAZUS	Hazards United States
ID	Identity
K	Multiplier for different pipe types in HAZUS
km	kilometer
K1	Multiplier for different pipe types in ALA
ln	natural logarithm
m	meter
M_W	Moment magnitude
P	Probability
PCCP	Prestressed concrete cylinder pipe
PE	Polyethylene
PGA	Peak Ground Acceleration
PGD	Permanent Ground Displacement
PGV	Peak Ground Velocity
w/MC	With Monte Carlo Simulation

1. INTRODUCTION

From the beginning of the earth, earthquakes have always been one of the most catastrophic natural disasters. They affect society negatively not only during or shortly after they occurred, their effects on societies can be observed even in a long period. The length of this recovery period highly depends on the number of damages that occurred in the infrastructure and lifeline systems of the cities. As being parts of the lifeline systems in a city, potable water systems, wastewater systems, electricity systems, etc. are vital for human life. Hence, the impediments in the serviceability of these lifeline systems put people's lives in danger even after an earthquake. Because, in the absence of water, contagious diseases and a lack of good hygiene become the most crucial parameters which threaten people's health after an earthquake. Especially, in the biggest metropolitan cities in the world such as Istanbul, Mexico City, etc. which are located in earthquake-prone regions, the serviceability rates of these lifeline systems have become more important than ever. Being home to millions of people and the center of the economic centers of a country makes these metropolitan cities more intolerable to the negative effects of the earthquakes. Therefore, studies to reduce negative effects and guess the serviceability of a lifeline system after an earthquake has gained major importance.

Being located on active faults, Turkey has always been encountered major earthquakes. 1939 Erzincan earthquake (Mw=7.8), 1942 Niksar - Erbaa Earthquake (Mw = 7.0), 1943 Tosya – Ladik Earthquake (Mw=7.2), 1944 Bolu - Gerede Earthquake (Mw=7.2), 1966 Varto Earthquake (Mw=6.9), 1999 Izmit Earthquake (Mw=7.6) and 1999 Duzce Earthquake (Mw=7.2) are some of the events occurred in the last century. Earthquakes are inevitable, but to reduce the effects of an earthquake depends on the precautions taken and these precautions do not only include saving lives in the buildings undergo earthquake loadings, but also should include protecting the serviceability of the lifeline systems which will become the most crucial parameters to keep a society healthy and provide a short recovery period after an earthquake.

In this study, the repair numbers of the water pipeline system in Zeytinburnu province due to a scenario earthquake will be examined according to the algorithms suggested by HAZUS-FEMA and American Lifeline Alliance (ALA). This section will continue with the literature review and the scope and objective of the thesis.

1.1. Literature Review

Studies on pipeline damages due to an earthquake have started in the 1970s. PGA-based research by Katayama et al was studied by using the data from six different earthquakes in 1975 [1]. This research covers the study of asbestos cement (AC) and segmented cast iron (CI) pipes in poor, average, and good soil conditions.

The first study on pipeline damage due to an earthquake by using PGV-based fragility relation was performed by Barenberg [2]. In Barenberg's study, the damages on pipes were assumed due to both the velocity-induced ground strain and permanent ground displacement (PGD). The damage type such as break or joint failure etc. was not taken into consideration in Barenberg's study. Then, O'Rourke and Ayala (1993), studied pipeline damages by using the PGV parameter [3]. O'Rourke and Ayala (1993) expanded the data catalog that was used by Barenberg by adding seven earthquakes, two of them are Mexican and five of them are U.S. earthquakes. This study was adopted by the loss assessment methodology HAZUS-MH of FEMA [4]. In this study, they examined only the damage due to earthquake wave propagation. Their study also includes different pipe material types, specifically cast iron (CI) pipes, concrete pipes, asbestos cement (AC) pipes and prestressed concrete cylinder pipes (PCCP). American Lifeline Alliance (ALA) also used PGV as an earthquake intensity parameter to estimate the probability of water pipeline damages due to an earthquake [5]. Eskandari et al. studied pipeline damages due to ground shaking and ground failure simultaneously [6].

In this study, the pipe failures due to ground shakings will be taken into consideration. Both of the approaches performed by HAZUS and ALA will be compared. Moreover, the results of the pipeline damage probabilities and the number of repairs according to these two methods are recalculated by applying the Monte Carlo simulation method.

1.2. Scope and Objective of the Thesis

To minimize the negative effects of an earthquake, it is crucial to minimize the recovery period after an earthquake. This recovery period is directly related to the number of damages that occurred in infrastructure and lifeline systems. In this study, to calculate the total number of repairs which is defined as the sum of the leaks and the breaks in the pipeline system, the approaches adopted by HAZUS-FEMA and by the American Lifeline Alliance (ALA) are compared. Since the earthquakes are unpredictable and contain a lot of uncertainties, Monte Carlo simulation is applied to the methods of HAZUS and ALA to reduce the uncertainties to some extent. The results of these two methods through Monte Carlo simulation are also compared. Since the results obtained by Monte Carlo sampling are dependent on the sampling number, the effects of the sampling number on the results are also evaluated in the sensitivity analysis section.

While performing the study, an earthquake on the Main Marmara Fault is assumed to occur and the study is conducted under the effects of this scenario earthquake. The parameters of the scenario earthquake are given in the case study section in detail.

The study is performed for four different types of materials, namely, concrete, bellmouth concrete, steel, and polyethylene. Concrete and bellmouth concrete pipes show brittle characteristics, whereas steel and polyethylene pipes show ductile characteristics. Therefore, in the study, the effects of using ductile pipes and the effects of using brittle pipes on damages due to ground shaking are also compared.

2. METHODOLOGY

In this study, repair rates which are defined as the repair numbers per unit length of a pipe are calculated by using the approaches adopted by both HAZUS-FEMA(2003) and American Lifeline Alliance (ALA-2001). HAZUS uses PGV-based algorithms suggested by O'Rourke and Ayala (1993). The repair rate is calculated by Equation 2.1.

$$Repair\ Rate\ (repairs\ per\ 1,000\ meters\ of\ a\ pipe) \cong 0.0001 \times (PGV)^{2.25} \tag{2.1}$$

In Equation 2.1 PGV is expressed in centimeters per second. Equation 2.1 is valid for brittle materials such as asbestos cement, concrete, and cast iron (CI) pipes. Since the ductile pipelines have 30 % of the vulnerability of brittle pipelines, Equation 2.1 should be multiplied by a factor of 0.3 to adapt it for ductile materials such as steel, ductile iron, PVC, etc as indicated in Equation 2.2.

$$Repair\ Rate\ (repairs\ per\ 1,000\ meters\ of\ a\ pipe) \cong 0.3 \times 0.0001 \times (PGV)^{2.25} \tag{2.2}$$

American Lifelines Alliance (ALA) also uses PGV-based algorithms depending on 81 data points and most of the pipes are CI pipes. The relation suggested by ALA is followed in Equation 2.3. In Equation 2.3, PGV is given in inches per second.

$$Repair\ Rate\ (repairs\ per\ 1,000\ feet\ of\ a\ pipe) \cong K1 \times 0.00187 \times (PGV) \tag{2.3}$$

The version of Equation 2.3 in SI units is given in Equation 2.4 where PGV is given in centimeters per second [7].

$$Repair\ Rate\ (repairs\ per\ 1,000\ meters\ of\ a\ pipe) \cong K1 \times 0.002416 \times (PGV) \quad (2.4)$$

K1 multiplier in Equations 2.3 and 2.4 is used to adapt the equations for different pipe materials. Table 2.1 shows the multiplier values (K1) for different pipe materials in ALA.

Table 2.1. Ground shaking - constants for fragility curves (ALA-2001).

Pipe Material	**Joint Type**	**Soils**	**Diam.**	**K1**	**Reference Section**
Cast Iron	Cement	All	Small	1.00	4.4.2
Cast Iron	Cement	Corrosive	Small	1.40	4.4.2
Cast Iron	Cement	Non-corrosive	Small	0.70	4.4.2
Cast Iron	Rubber gasket	All	Small	0.80	4.4.2
Welded Steel	Lap-Arc Welded	All	Small	0.60	4.4.4
Welded Steel	Lap-Arc Welded	Corrosive	Small	0.90	4.4.4
Welded Steel	Lap-Arc Welded	Non-corrosive	Small	0.30	4.4.4
Welded Steel	Lap-Arc Welded	All	Large	0.15	4.4.4
Welded Steel	Rubber gasket	All	Small	0.70	4.4.6
Welded Steel	Screwed	All	Small	1.30	4.4.6 A.3.11
Welded Steel	Riveted	All	Small	1.30	4.4.6
Asbestos Cement	Rubber gasket	All	Small	0.50	4.4.3 4.4.5
Asbestos Cement	Cement	All	Small	1.00	4.4.3
Cocrete w/Stl Cyl.	Lap-Arc Welded	All	Large	0.70	4.4.6
Cocrete w/Stl Cyl.	Cement	All	Large	1.00	4.4.6
Cocrete w/Stl Cyl.	Rubber Gasket	All	Large	0.80	4.4.6
PVC	Rubber gasket	All	Small	0.50	4.4.6
Ductile Iron	Rubber gasket	All	Small	0.50	4.4.5 4.4.6

The four types of pipe materials and two types of diameters used in this study are given in Table 2.2. Small diameter refers to the diameters ranging from 4 to 12 inches and large diameter refers to 16 inches or larger, respectively [5].

Table 2.2. Four types of pipe materials and two types of diameters.

Material	Concrete	Bellmouth Concrete	Steel	Polyethylene (PE)
Diameter	Large	Small	Large	Small
ALA K1 coefficient	1.00	0.80	0.004	0.30
HAZUS K coefficient	1.00	1.00	0.30	0.30

The coefficient for large diameter concrete pipe is the same as that for large-diameter concrete w/stl cyl. pipe with cement joint, in all soil types in Table 2.1. The coefficient for small diameter bellmouth concrete pipe is the same as that for small diameter cast iron pipe with rubber gasket joint in all soils type. The coefficient for large diameter steel pipe is the same as $0.5 \times 0.01 \times K1 = 0.8$ (cast iron, rubber gasket, all soils, small). This is scaled by 0.5 for large-diameter pipe and also scaled by 0.01 as per ALA Part 1-Guideline for Welded Steel Arc Welded X Grade. The coefficient for small diameter polyethylene (PE) pipe is the same as that for small diameter welded steel with lap-arc welded joint in non-corrosive soil type.

2.1. Poisson Process

To find the failure probability of an individual pipeline, Poisson probability distribution is utilized. The Poisson probability equation which gives the probability of the random variable N(t) being equal to n is given in Equation 2.5.

$$P(N(t) = n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{2.5}$$

where n is the number of occurrence, e is Euler's number, t is the time or space interval and λ is the average rate of events.

To adapt Equation 2.5 to estimate the failure probability (fp) of a pipe, we subtract the zero event case from all of the cases. In other words, the probability of failure is equal to the probability of at least one failure which is calculated by subtracting the probability of zero events from 1. If we equate n to 0 and substitute it into Equation 2.5 and subtract it from 1, we find the probability of at least 1 failure which is given in Equation 2.6.

$$fp = 1 - \frac{(\lambda t)^0 e^{-\lambda t}}{0!} \tag{2.6}$$

Equation 2.6 can be simplified to Equation 2.7.

$$fp = 1 - e^{-\lambda t} \tag{2.7}$$

where, λ is the repair rate and t is the segment length of a pipe in a grid.

In HAZUS and ALA, Equation 2.7 is used to find the failure probability of a pipe segment. To find the number of leaks and breaks, first, the repair rates of each grid segment are multiplied with the corresponding segment lengths of the pipes to find the number of repairs for each pipe segment. Then the calculated repair number of all pipe segments is summed to find the total number of repairs for the pipeline system of interest. At this stage, it is assumed that 80% of the repairs are leaks and 20% is break based on the past empirical studies.

2.2. Monte Carlo Simulation

Monte Carlo simulation is a computerized mathematical technique helping people to predict the results of quantitative analysis which contains various uncertainties. It is used in a lot of fields such as finance, engineering, supply chain, etc. In this study, we do not directly use the algorithms suggested by HAZUS-FEMA and ALA to calculate number of repairs and probability of failure (damage), instead, we recalculate the results by incorporating the Monte Carlo sampling technique into HAZUS-FEMA and ALA. By selecting a large sample number in Monte Carlo simulation, the calculated results (number of repairs and probabilities) become more rational which are likely to occur in reality.

While incorporating the Monte Carlo sampling into HAZUS and ALA, first the failure probability of a pipe segment in a grid is calculated by using Equation 2.7, then a random number between 0 and 1 is selected from the uniform probability distribution. If the selected random number is smaller than the failure (damage) probability (fp) of the pipe segment in that grid, it is assumed that the pipe does not fail in that grid, then a new random number is selected again until it exceeds the failure probability. Once the selected random number is bigger than the failure probability in that grid, it is assumed that the pipe in that grid fails. After failure, it is important to specify whether the failure type is a leak or a break. To determine the failure type, namely, break or leak, a new random number between 0 and 100 is selected from the uniform probability distribution. It is assumed that 80% of the pipe failures due to ground shakings are leaks and 20% of the failures are breaks [4]. Hence, if the new selected number is between 0 and 80, it is assumed that the pipe undergoes leak, otherwise, break. This procedure is repeated for 50,000 times for the grid. Once it is completed for one grid, we continue to apply these steps to the next grid containing a pipe segment. In this way, all of the grids are taken into consideration successively. Figure 2.1 shows the flowchart of the steps explained above.

The probability of damage (failure), probability of leak, and probability of break are calculated as follows.

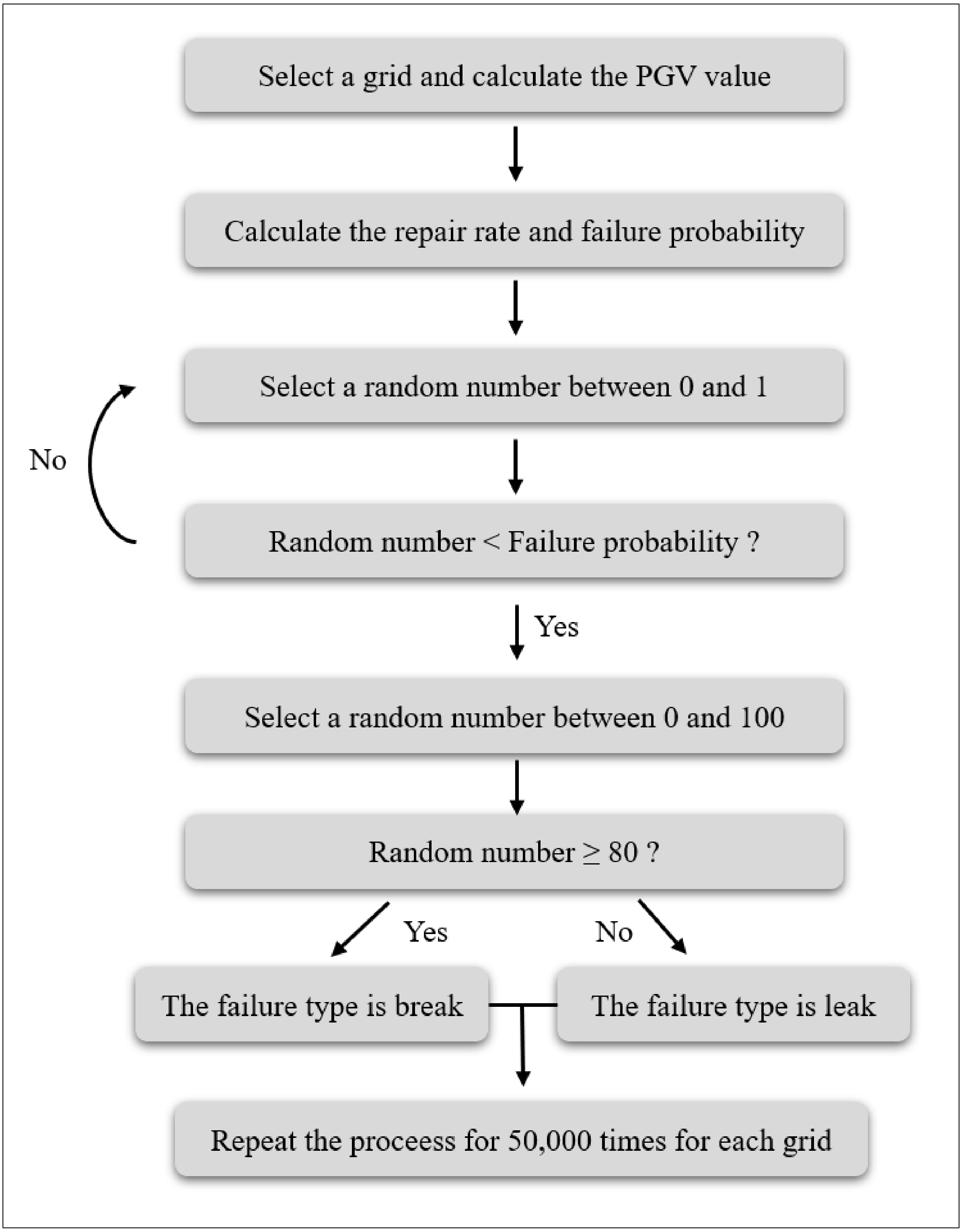


Figure 2.1. The flowchart of the implementation of Monte Carlo Simulation.

Let NS be the total sample number of the Monte Carlo simulation, NL be the number of leaks and NB be the number of breaks. The probability of leak, P(leak), is calculated by dividing the number of leaks (NL) by the total sample number (NS). Similarly, the probability of breaks, P(break), is calculated by dividing the number of breaks (NB) by the total sample number (NS). The probability of failure, P(failure), is calculated by summing P(leak) and P(break). The respective equations are given as follows.

$$P(leak) = \frac{NL}{NS}, \; and \; P(break) = \frac{NB}{NS} \tag{2.8}$$

$$P(failure) = P(leak) + P(break) \tag{2.9}$$

where NS is selected as 50,000 in this study.

To calculate the number of leaks, the number of breaks, and the number of total repairs, Equation 2.7 is rearranged to solve for λt which is the repair number. If we rearrange Equation 2.7, we get Equation 2.10.

$$\lambda t = -ln(1 - fp) \tag{2.10}$$

If we substitute $P(leak)$ into fp in Equation 2.10, we get the number of leaks. Similarly, we get the number of breaks and number of total repairs by substituting $P(break)$ and $P(failure)$ into Equation 2.10, respectively. Equations 2.11 to 2.13 give the number of leaks, the number of breaks, and the number of total repairs, respectively.

$$Number\ of\ Leaks = -ln(1 - P(leak)) \tag{2.11}$$

$$Number\ of\ Breaks = -ln(1 - P(break)) \tag{2.12}$$

$$Number\ of\ Repairs(leak + break) = -ln(1 - P(failure)) \tag{2.13}$$

The calculated leak, break, and total repair numbers of all pipe segments are summed to find the corresponding number of repairs for the pipeline system of interest.

3. CASE STUDY

We perform this research on a generic study for Zeytinburnu province in Istanbul. The grids where the pipes are located are selected such that each grid has approximately 420m by 555m dimensions. Figure 3.1 shows the location of the 68 grids with an ID number on them. In Figure 3.1 and in the following geographical figures, although the grid sizes are the same, they seem different due to overlapping of the grids. In other words, some grids block others visually. But, this situation does not affect the results (number of repairs and failure probabilities). The pipe inventory of Zeytinburnu province is taken from the Istanbul Metropolitan Municipality database. The length of the pipeline system to be analyzed is 197.9 km. Figure 3.2 shows the pipe length distribution in each grid.

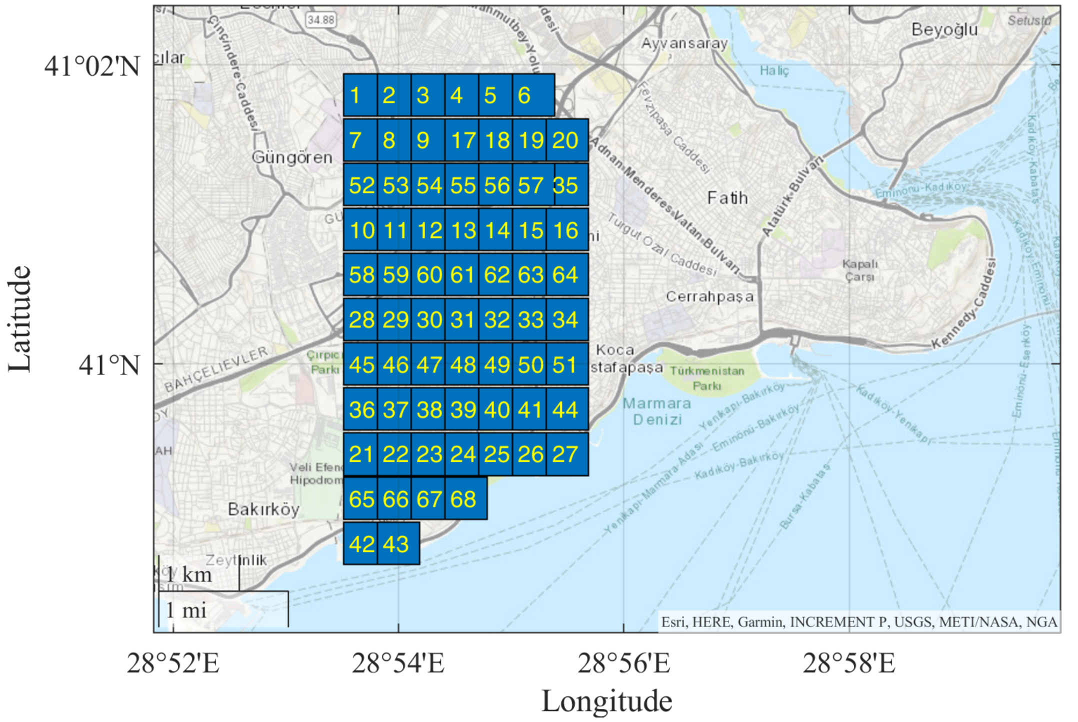


Figure 3.1. The grid locations and their ID numbers in Zeytinurnu location.

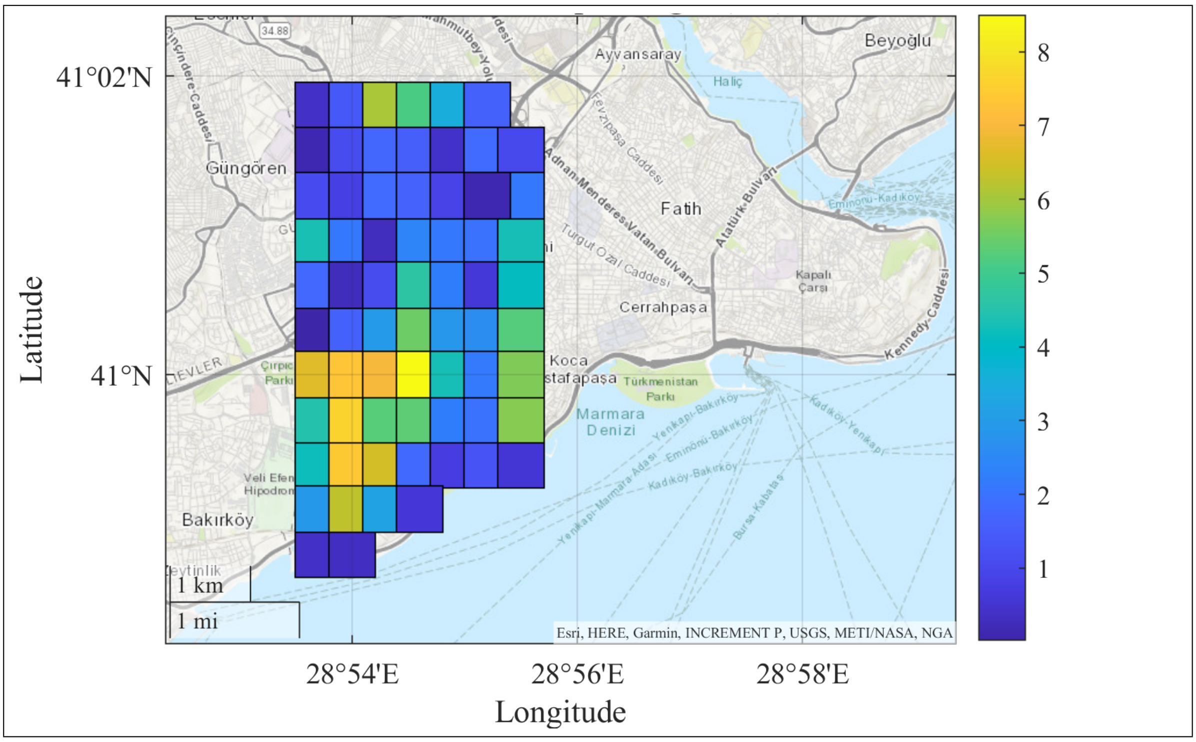


Figure 3.2. Distribution of pipe lengths in kilometers.

3.1. The Scenario Earthquake

To continue the study, it is required to generate a scenario earthquake that is likely to occur in the Marmara Sea region to get probable PGV values in the grids where the pipes are located. The earthquake generated, thanks to ELER software by Kandilli Observatory and Earthquake Research Institute [8]., has the same earthquake parameters as in the Updating Project of the Possible Earthquake Losses Forecast of Istanbul (2009) by Istanbul Metropolitan Municipality and Kandilli Observatory and Earthquake Research Institute. An earthquake with magnitude Mw=7.5 is assumed to occur on the segments which have not broken yet on the Main Marmara Fault. Figure 3.3 shows the associated fault segments of the Main Marmara Fault with red lines and the epicenter of the scenario earthquake that is marked with a red star. The assumed scenario earthquake is equivalent to a controlling scenario (by using deaggregation) of the probabilistic seismic hazard analysis with a level of 50% exceedance in 50 years [9].

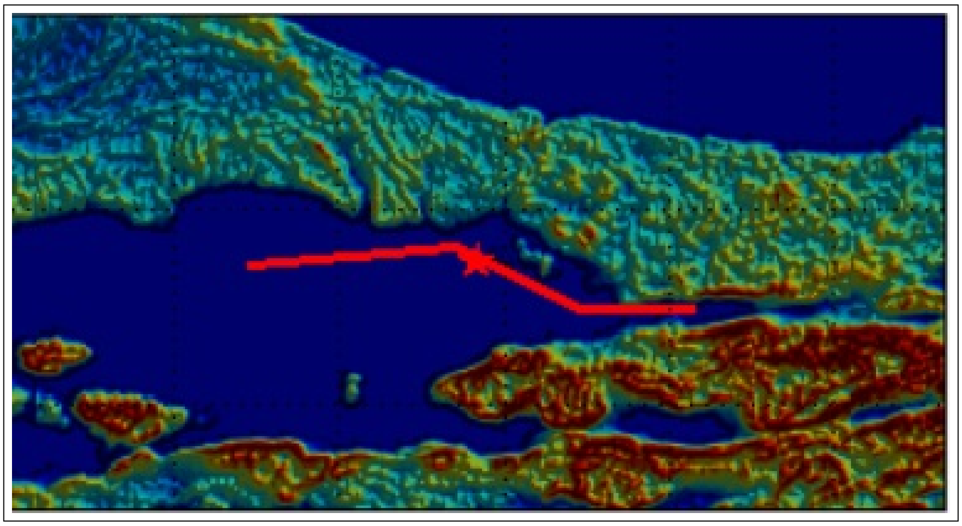


Figure 3.3. Fault and epicenter of the scenario event (from ELER). Epicenter is shown by red star and the associated fault segments are shown with red lines for the scenario earthquake.

The PGV intensity contour map generated by ELER software as a result of the scenario earthquake is given in Figure 3.4. The map also shows the coordinates of the earthquake epicenter. The PGV values in the grids are calculated by using the GMPE formula suggested by Chiou & Youngs, 2008. Figure 3.5 shows the corresponding PGV distribution values in each grid.

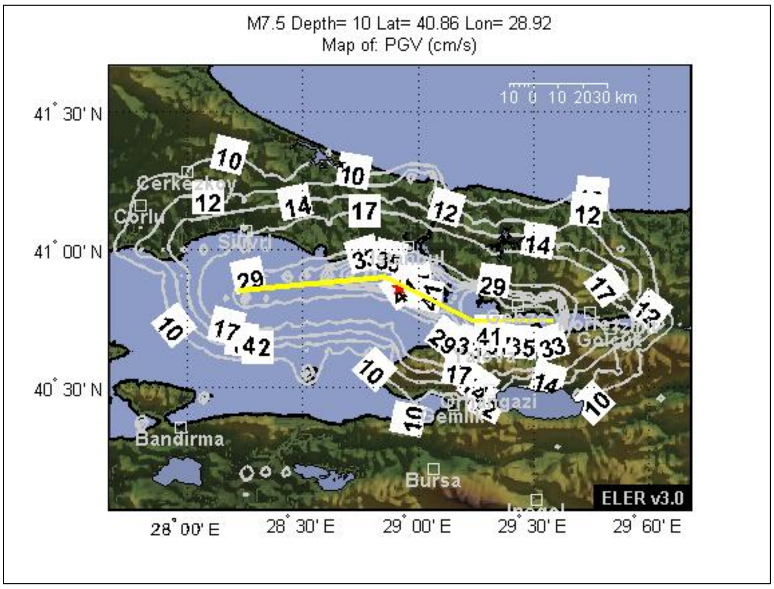


Figure 3.4. The PGV intensity contour map (from ELER).

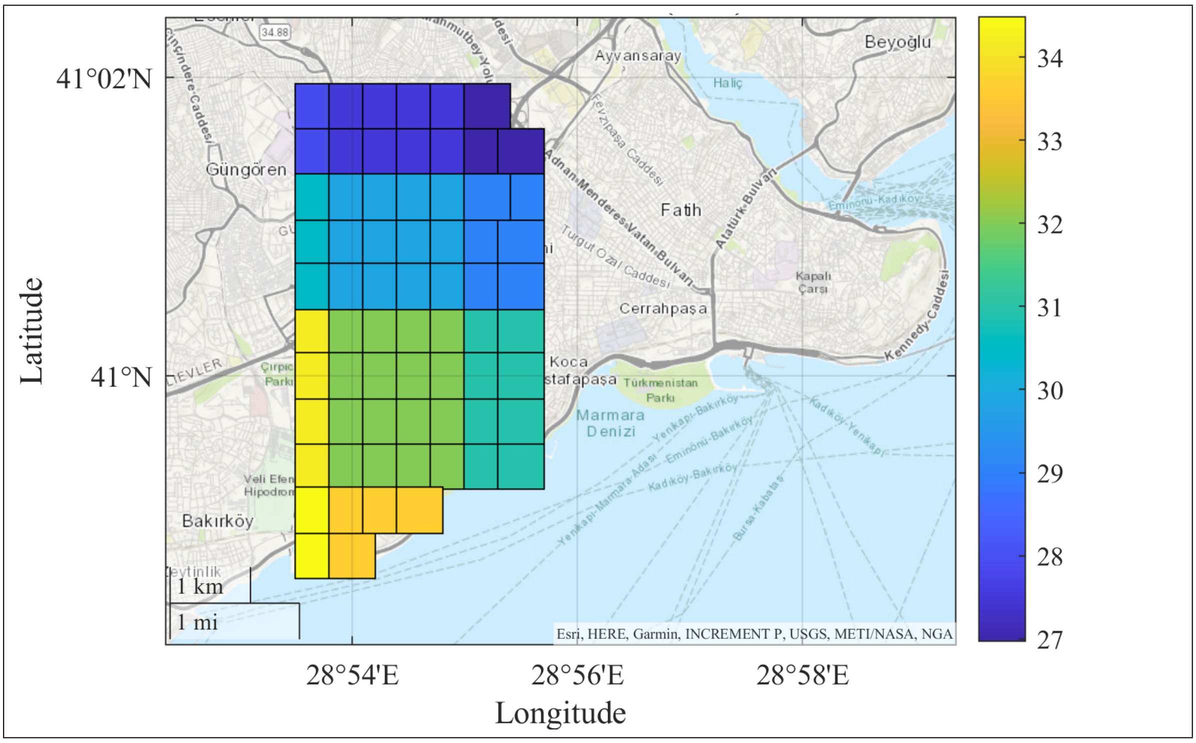


Figure 3.5. The Distribution of the PGV values in cm/s.

Bar type Figure 3.6 also shows the numeric values of the PGV and pipe lengths in each grid. It can be noted from Figure 3.6 that the PGV values in the grids are close to each other, whereas the pipe lengths in the grids are very dissimilar.

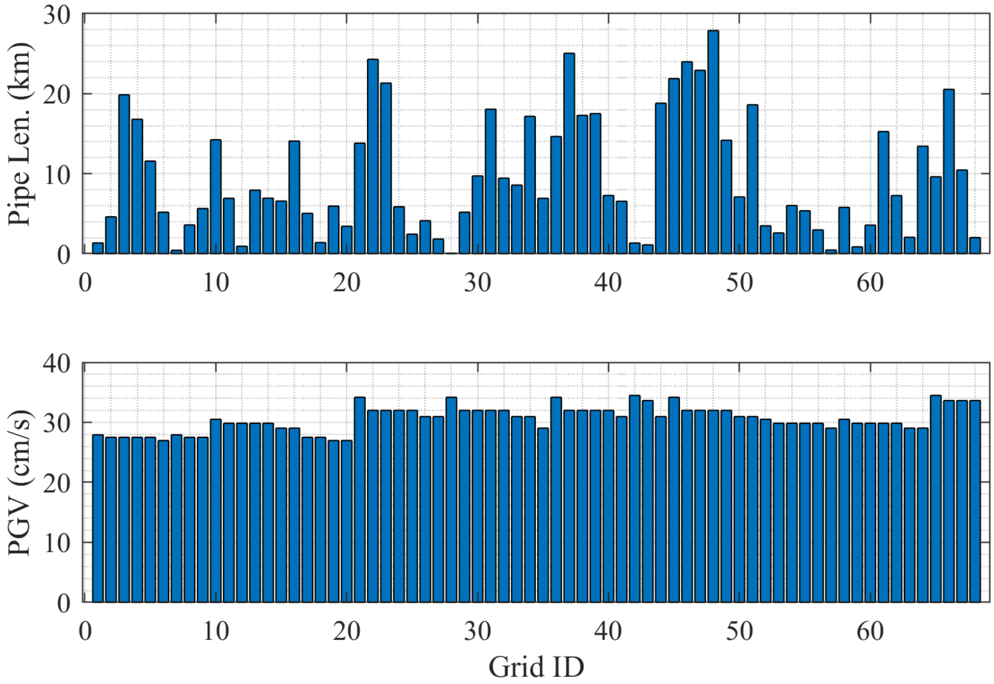


Figure 3.6. The pipe lengths (top) and PGV values (bottom) in each grid.

The PGV values in each grid are used to calculate the repair rate as mentioned in the methodology section. First, the repair numbers according to HAZUS-FEMA are calculated for four types of pipe materials, namely, concrete, bellmouth concrete, steel, and polyethylene. Then, the Monte Carlo simulation technique is incorporated into the HAZUS-FEMA method and the results are compared. The same steps are performed according to American Lifeline Alliance (ALA). The analyses are performed in MATLAB [10].

3.2. Results of HAZUS

3.2.1. Concrete Pipes and Bellmouth Concrete Pipes

Figures 3.7 and 3.10 show the results of the study for concrete and bellmouth concrete pipes. Since HAZUS uses the same multiplier for brittle materials, the results obtained for concrete pipes and bellmouth concrete pipes are the same. Figures 3.7 to 3.8 give the failure probabilities and the number of repairs obtained by the HAZUS algorithm and HAZUS algorithm through Monte Carlo sampling and the differences between HAZUS and HAZUS through Monte Carlo sampling. It can be noted from Figure 3.8 that 45 repairs consisting of 36 leaks and 9 breaks are observed by the HAZUS-FEMA approach, whereas 37 repairs consisting of 31 leaks and 9 breaks are observed by the HAZUS-FEMA approach through Monte Carlo simulation.

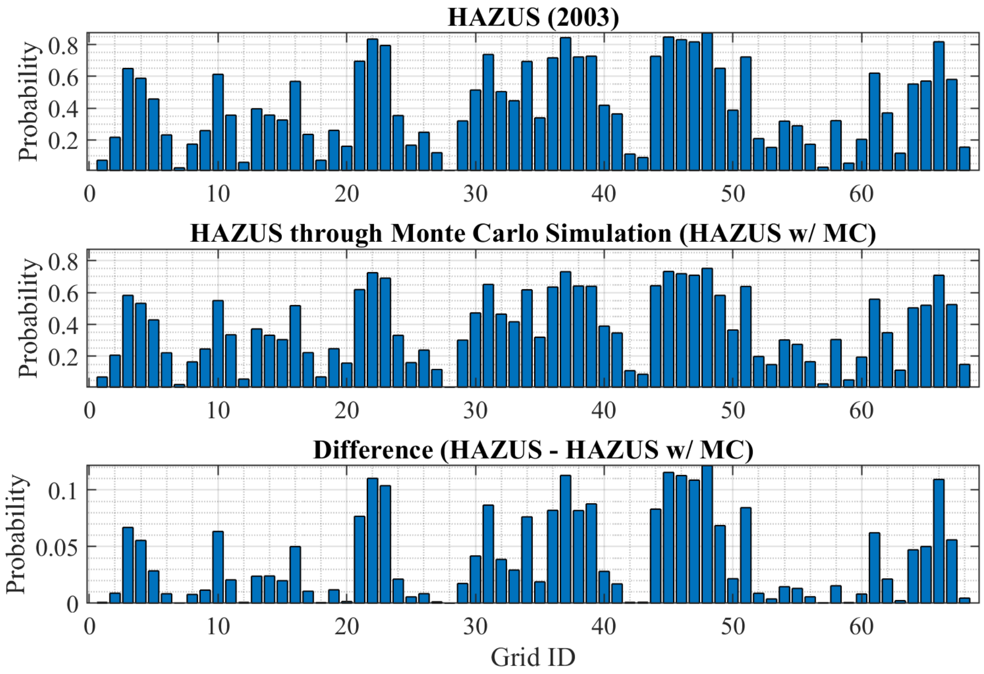


Figure 3.7. The probability of damage for concrete and bellmouth concrete pipes. The bottom figure shows the difference between damage probabilities calculated by using HAZUS and HAZUS through Monte Carlo simulation approaches.

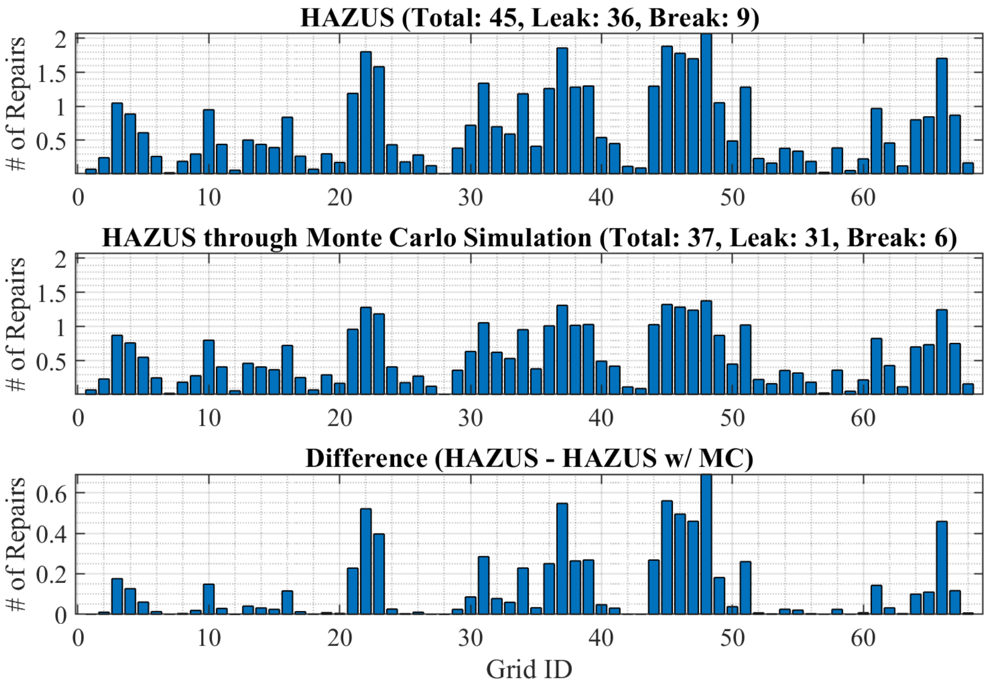


Figure 3.8. Number of repairs (leak + break) for concrete and bellmouth concrete pipes. The bottom figure shows the difference between number of repairs calculated by using HAZUS and HAZUS through Monte Carlo simulation approaches.

Geographical plots in Figure 3.9 and Figure 3.10 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

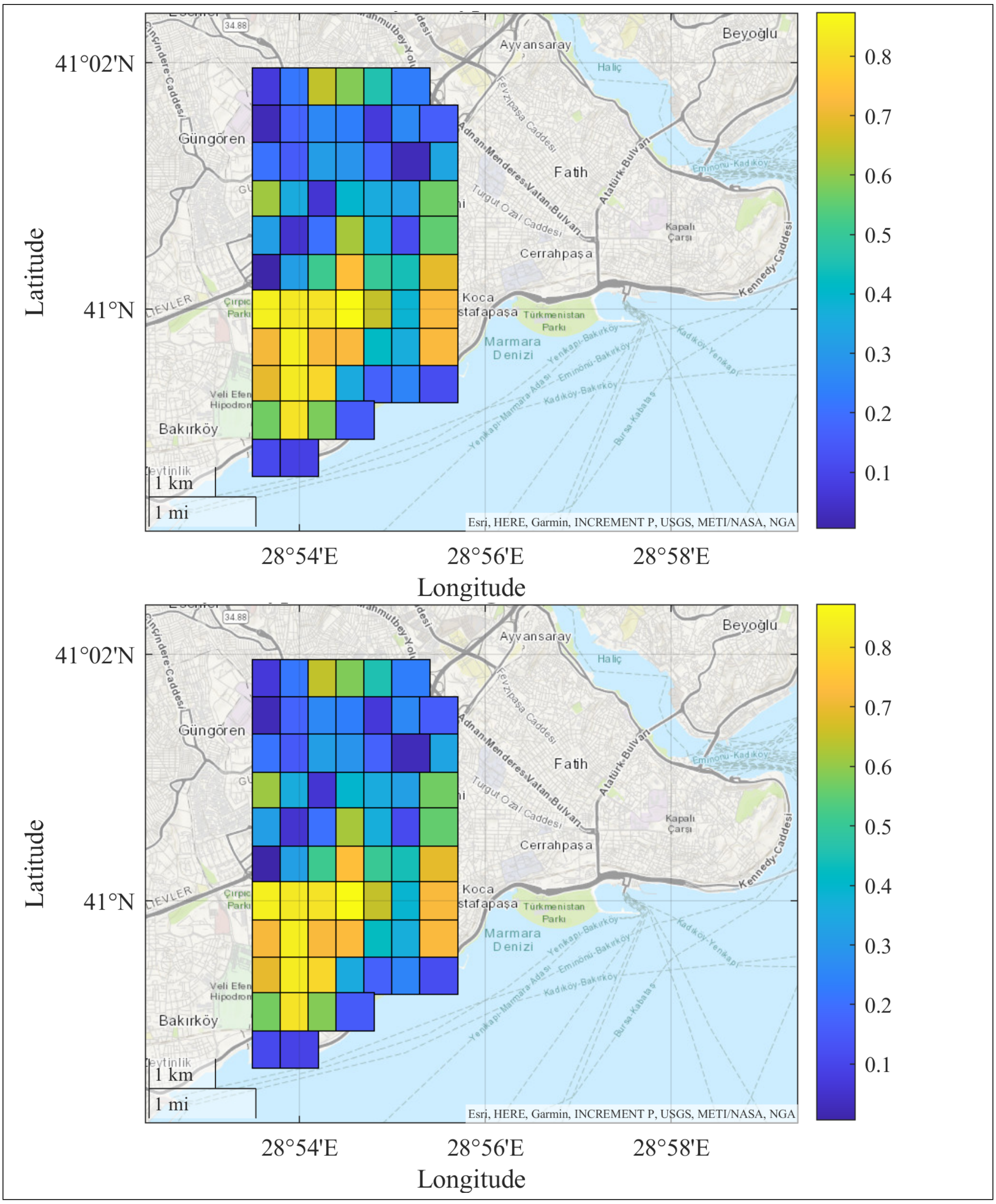


Figure 3.9. Maps of the probability of damage for concrete and bellmouth concrete pipes calculated by HAZUS (top) and HAZUS through Monte Carlo simulation approaches (bottom).

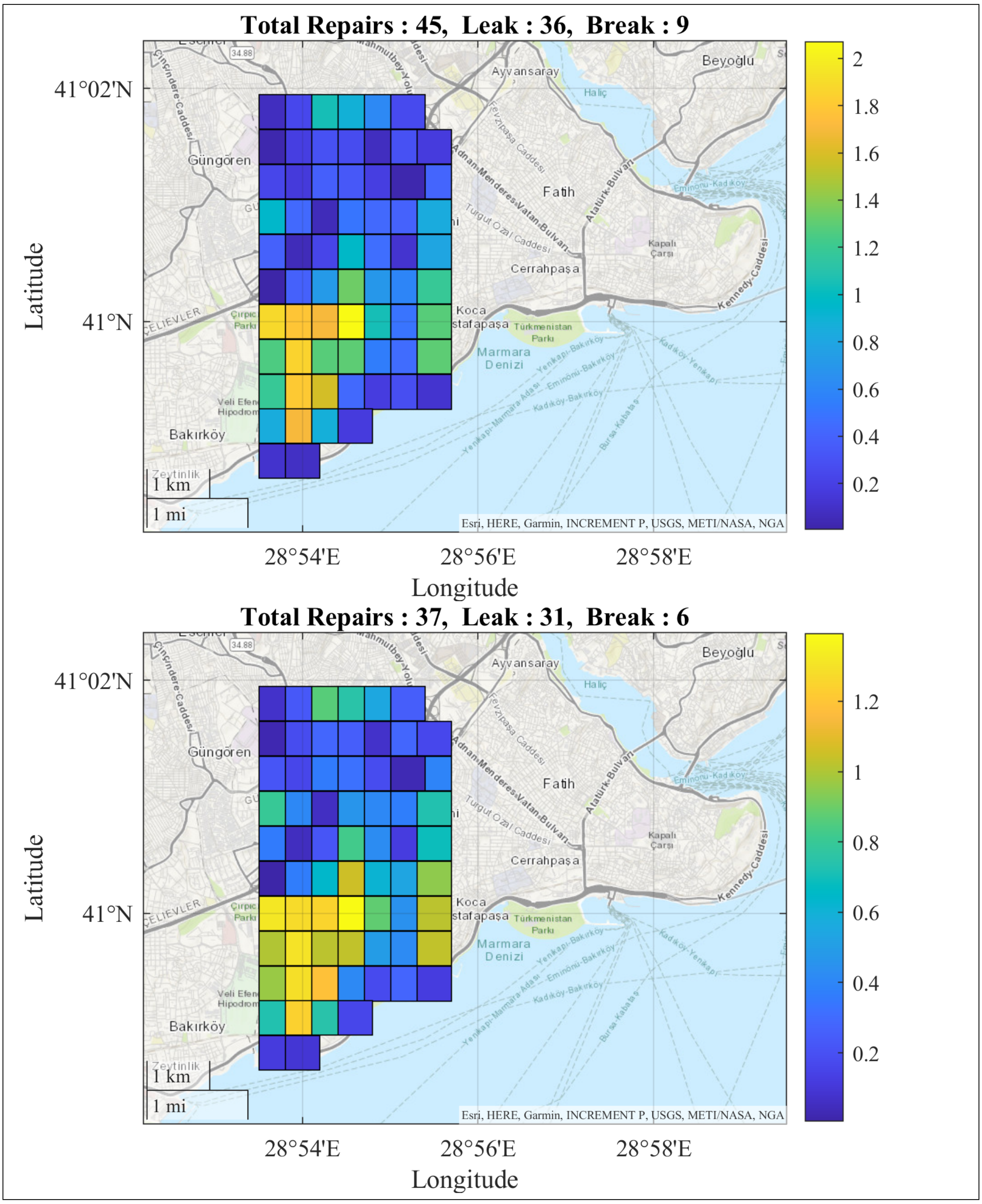


Figure 3.10. Maps of the number of repairs for concrete and bellmouth concrete pipes calculated by HAZUS (top) and HAZUS through Monte Carlo simulation approaches (bottom).

3.2.2. Steel Pipes and Polyethylene Pipes

Figures 3.11 to 3.14 show the results of this study for ductile pipes, namely, steel pipes and polyethylene pipes. Since HAZUS uses the same multiplier for ductile materials, the results obtained for steel pipes and polyethylene pipes are the same. Figures 3.11 and 3.12 give the failure probabilities and the repair numbers obtained by the HAZUS algorithm and HAZUS algorithm through Monte Carlo sampling and the differences between HAZUS and HAZUS through Monte Carlo sampling. It can be seen in Figure 3.12 that there are 11 leaks and 3 breaks observed by the HAZUS-FEMA approach, whereas, 10 leaks and 2 breaks are observed by the HAZUS-FEMA approach through Monte Carlo simulation. Since the steel pipes and polyethylene pipes show ductile characteristics, there is a drastic decrease in the failures compared to concrete and bellmouth concrete pipes.

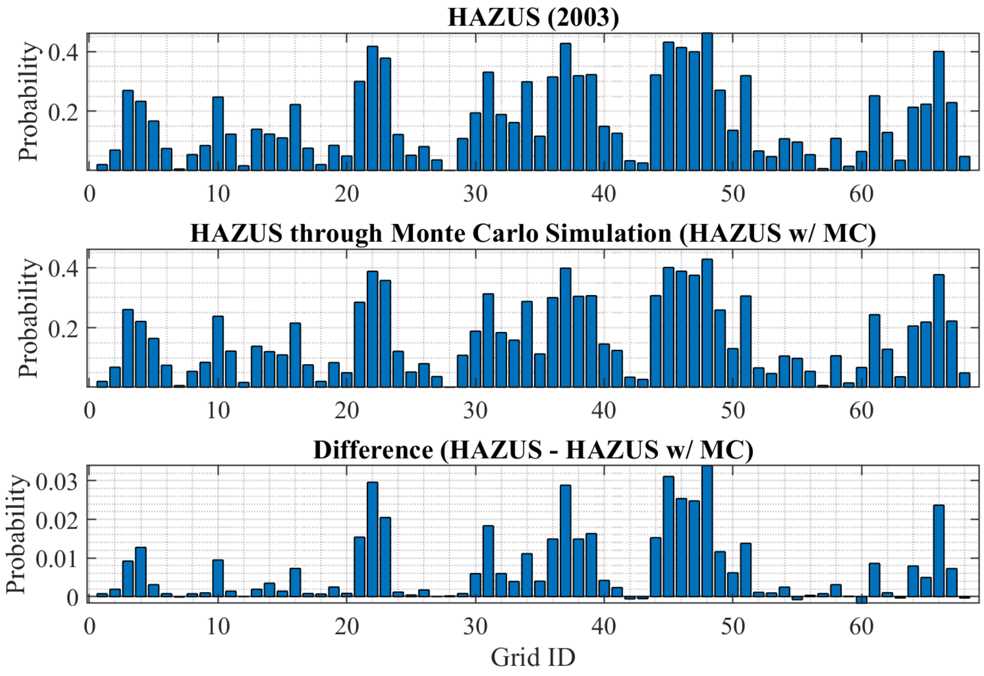


Figure 3.11. The probability of damage for steel and polyethylene pipes. The bottom figure shows the difference between damage probabilities calculated by using HAZUS and HAZUS through Monte Carlo simulation approaches.

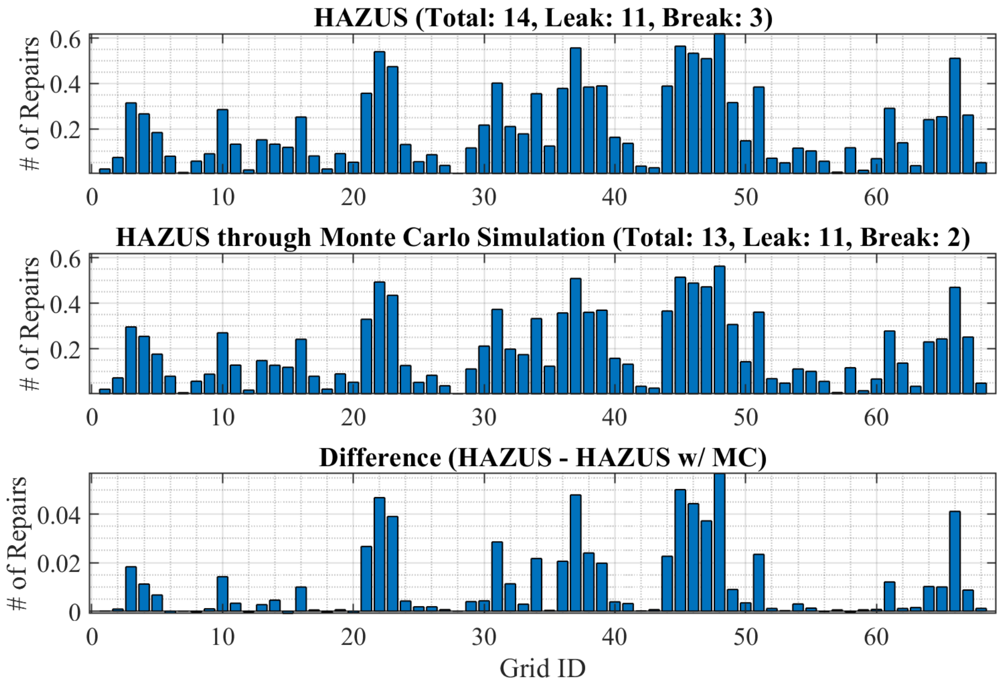


Figure 3.12. Number of repairs (leak + break) for steel and polyethylene pipes. The bottom figure shows the difference between number of repairs calculated by using HAZUS and HAZUS through Monte Carlo simulation approaches.

Geographical plots in Figure 3.13 and Figure 3.14 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

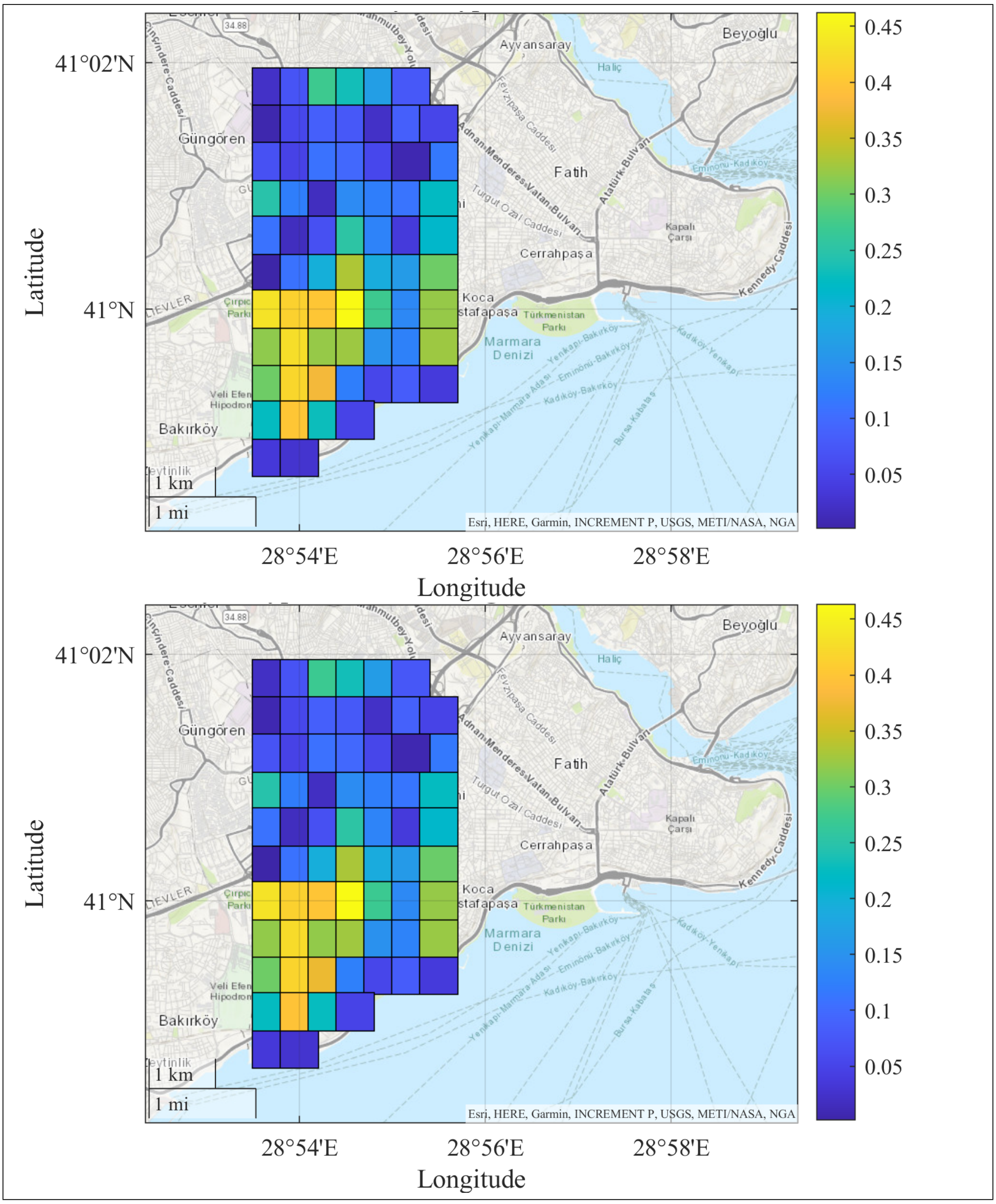
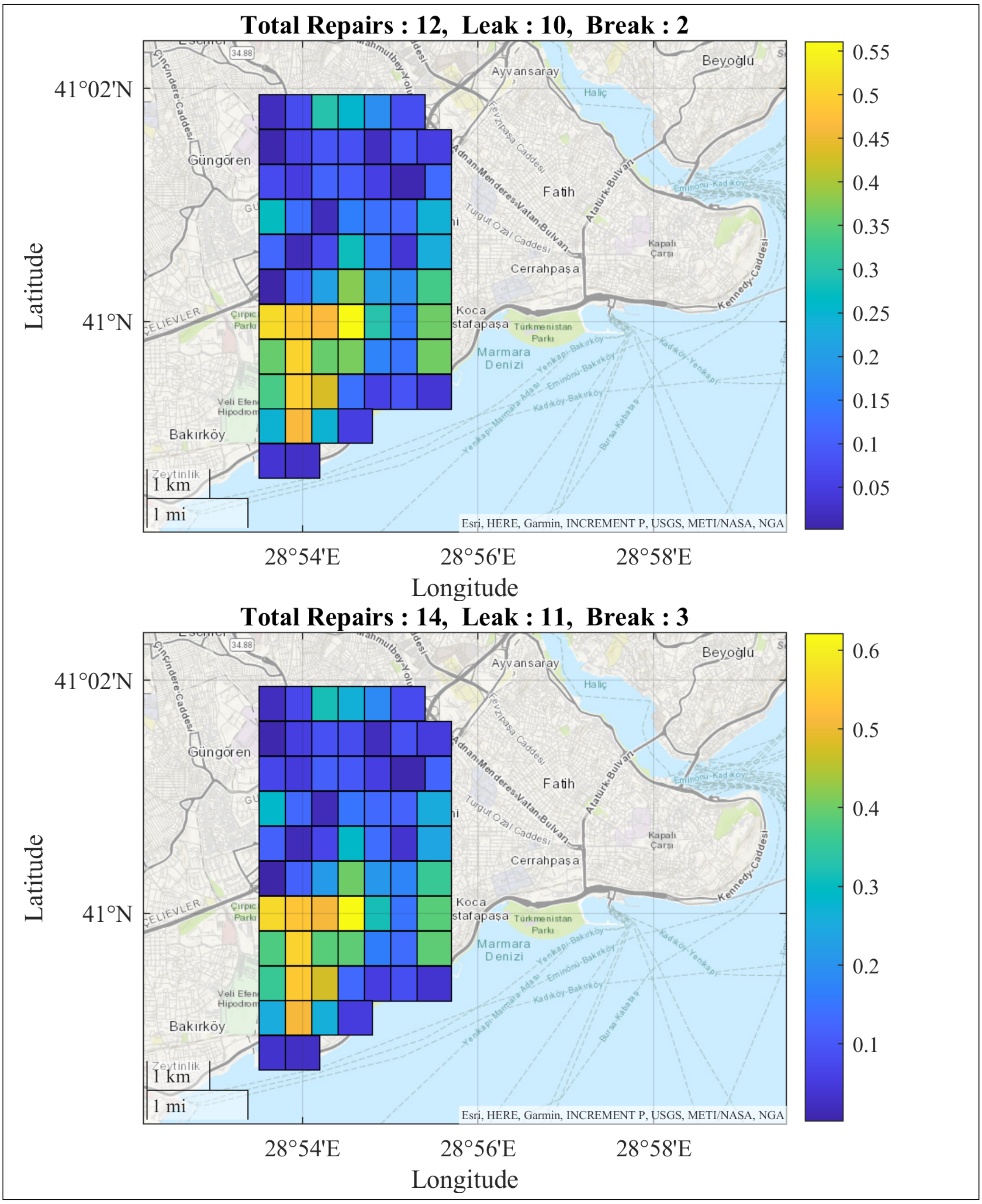


Figure 3.13. Maps of the probability of damage for steel and polyethylene pipes calculated by HAZUS (top) and HAZUS through Monte Carlo simulation approaches (bottom).



Total Repairs : 12, Leak : 10, Break : 2

Total Repairs : 14, Leak : 11, Break : 3

Figure 3.14. Maps of the number of repairs for steel and polyethylene pipes calculated by HAZUS (top) and HAZUS through Monte Carlo simulation approaches (bottom).

3.3. Results of ALA

3.3.1. Concrete Pipes

Figures 3.15 to 3.18 show the results of the study for concrete pipes. Figures 3.15 and 3.16 give the failure probabilities and the repair numbers obtained according to the algorithm suggested by American Lifeline Alliance (ALA) and ALA through Monte Carlo sampling and the differences between ALA and ALA through Monte Carlo sampling. It can be seen from Figure 3.16 that 15 repairs consisting of 12 leaks and 3 breaks are observed by the ALA approach, whereas 14 repairs consisting of 11 leaks and 3 breaks are observed by the ALA approach through Monte Carlo sampling. The results show that the repair numbers obtained by the ALA approach are one-third of the results obtained by the HAZUS- FEMA approach and the repair numbers obtained by the ALA approach through Monte Carlo sampling are approximately one-third of the results obtained by HAZUS- FEMA approach through Monte Carlo sampling.

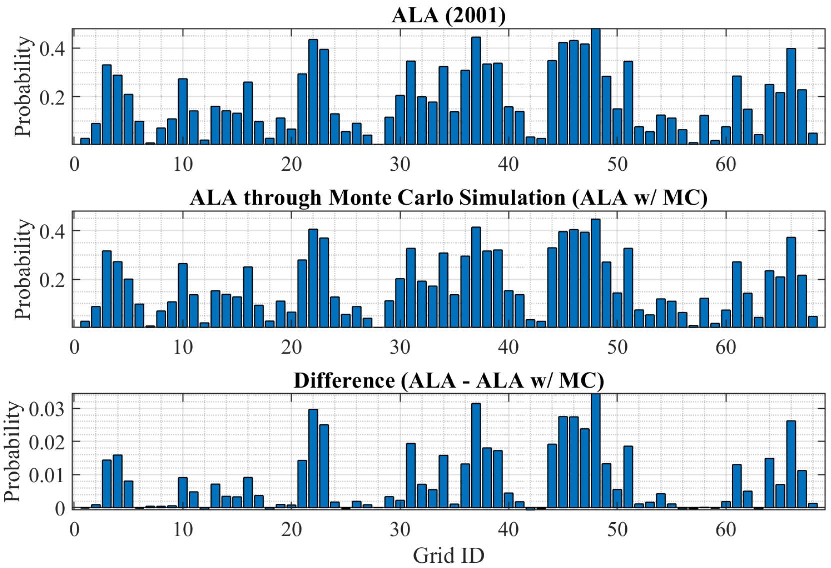


Figure 3.15. The probability of damage for concrete pipes. The bottom figure shows the difference between damage probabilities calculated by using ALA and ALA through Monte Carlo simulation approaches.

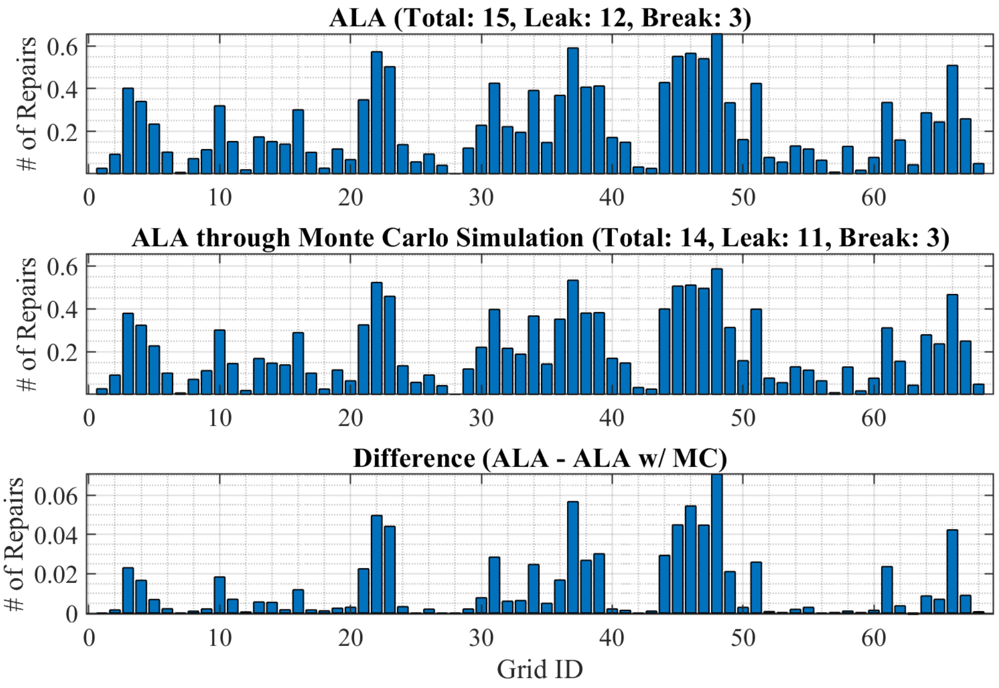


Figure 3.16. Number of repairs (leak + break) for concrete pipes. The bottom figure shows the difference between number of repairs calculated by using ALA and ALA through Monte Carlo simulation approaches.

Geographical plots in Figure 3.17 and Figure 3.18 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

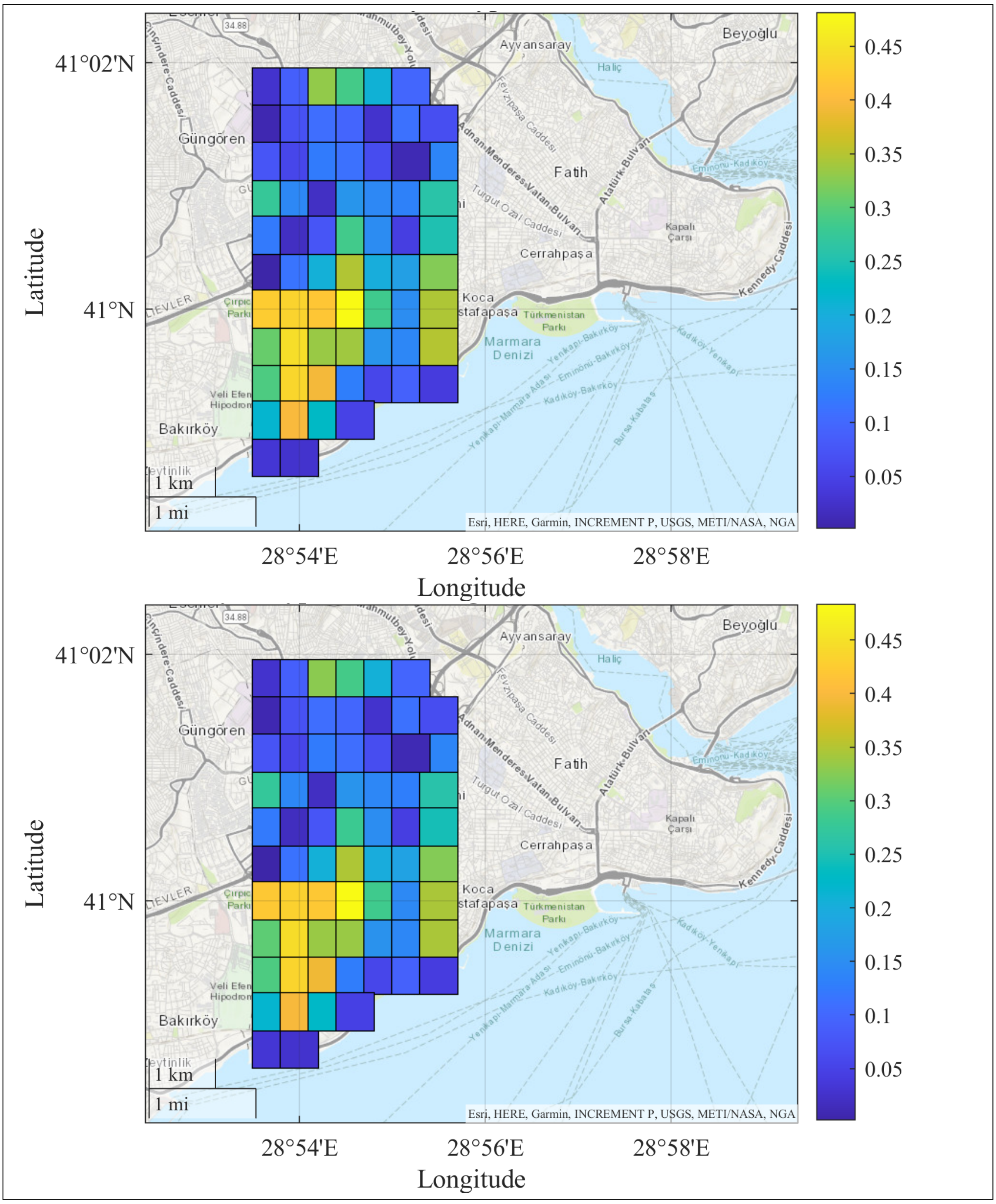


Figure 3.17. Maps of the probability of damage for concrete pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

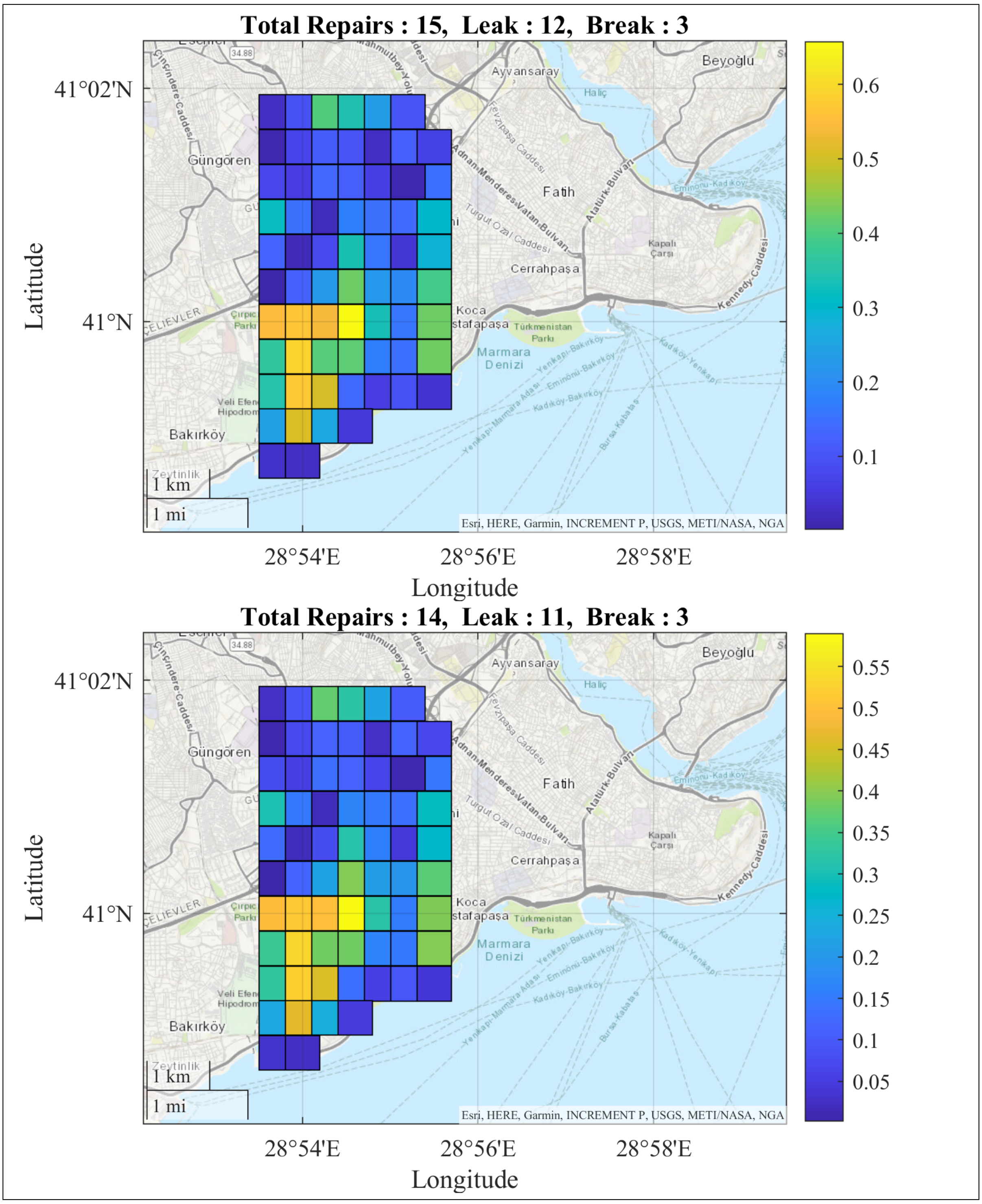


Figure 3.18. Maps of the number of repairs for concrete pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

3.3.2. Bellmouth Concrete Pipes

Figures 3.19 to 3.22 show the results of the study for bellmouth concrete pipes. Figures 3.19 and 3.20 give the failure probabilities and the number of repairs obtained by the American Lifeline Alliance (ALA) algorithm and ALA algorithm through Monte Carlo sampling and the differences between ALA and ALA through Monte Carlo sampling. Figure 3.22 indicates that 12 repairs consisting of 10 leaks and 2 breaks are observed by the ALA approach, whereas, 11 repairs consisting of 9 leaks and 2 breaks are observed by the ALA approach with Monte Carlo sampling.

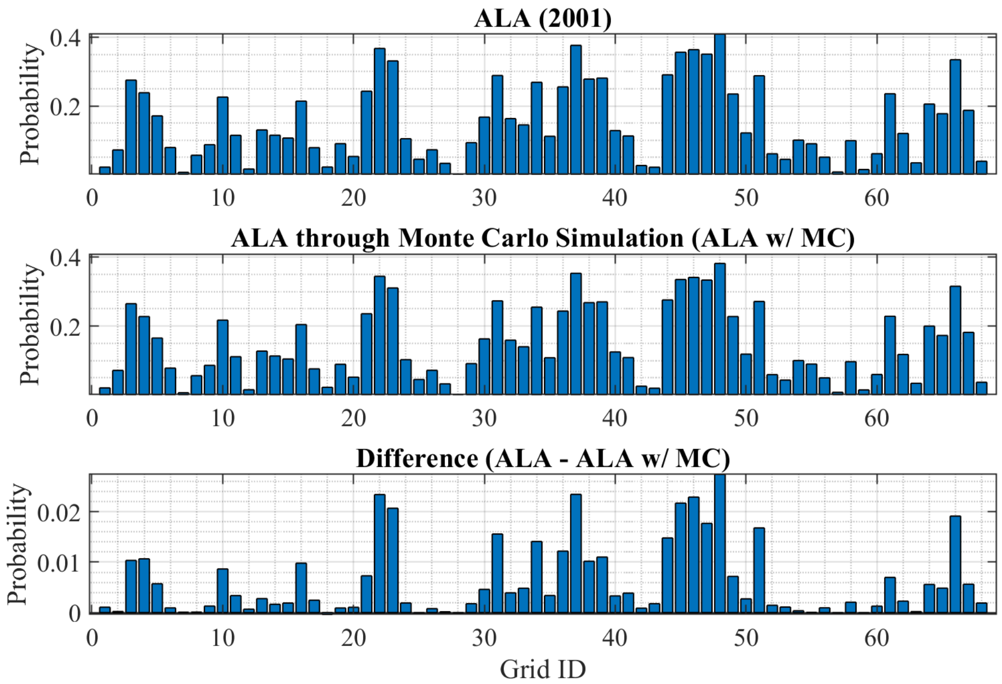


Figure 3.19. The probability of damage for bellmouth concrete pipes. The bottom figure shows the difference between damage probabilities calculated by using ALA and ALA through Monte Carlo simulation approaches.

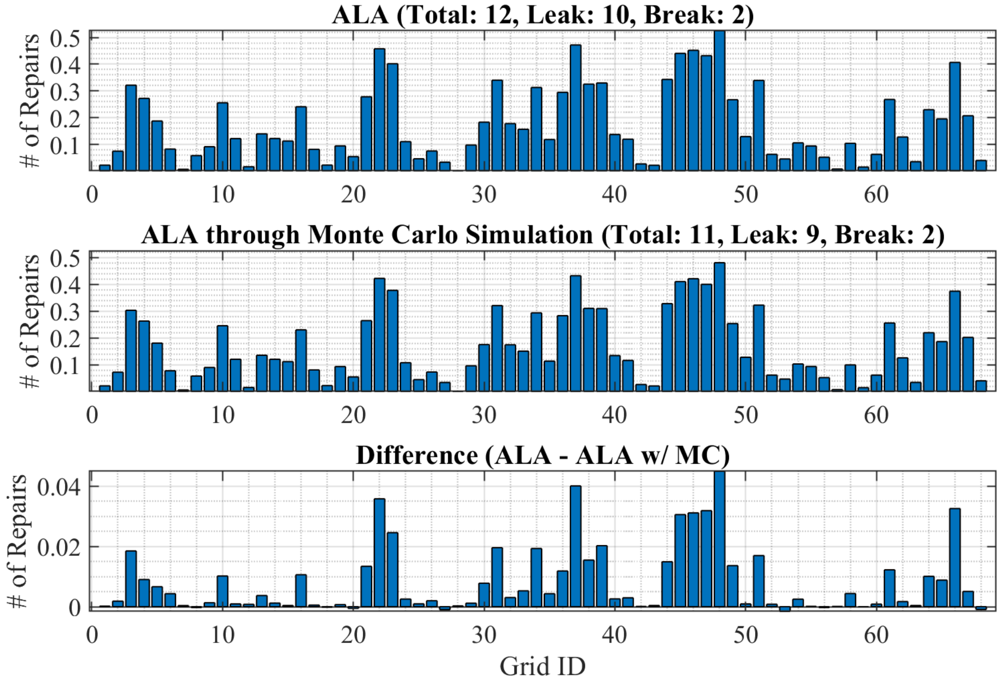


Figure 3.20. Number of repairs (leak + break) for bellmouth concrete pipes. The bottom figure shows the difference between number of repairs calculated by using ALA and ALA through Monte Carlo simulation approaches.

Geographical plots in Figure 3.21 and Figure 3.22 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

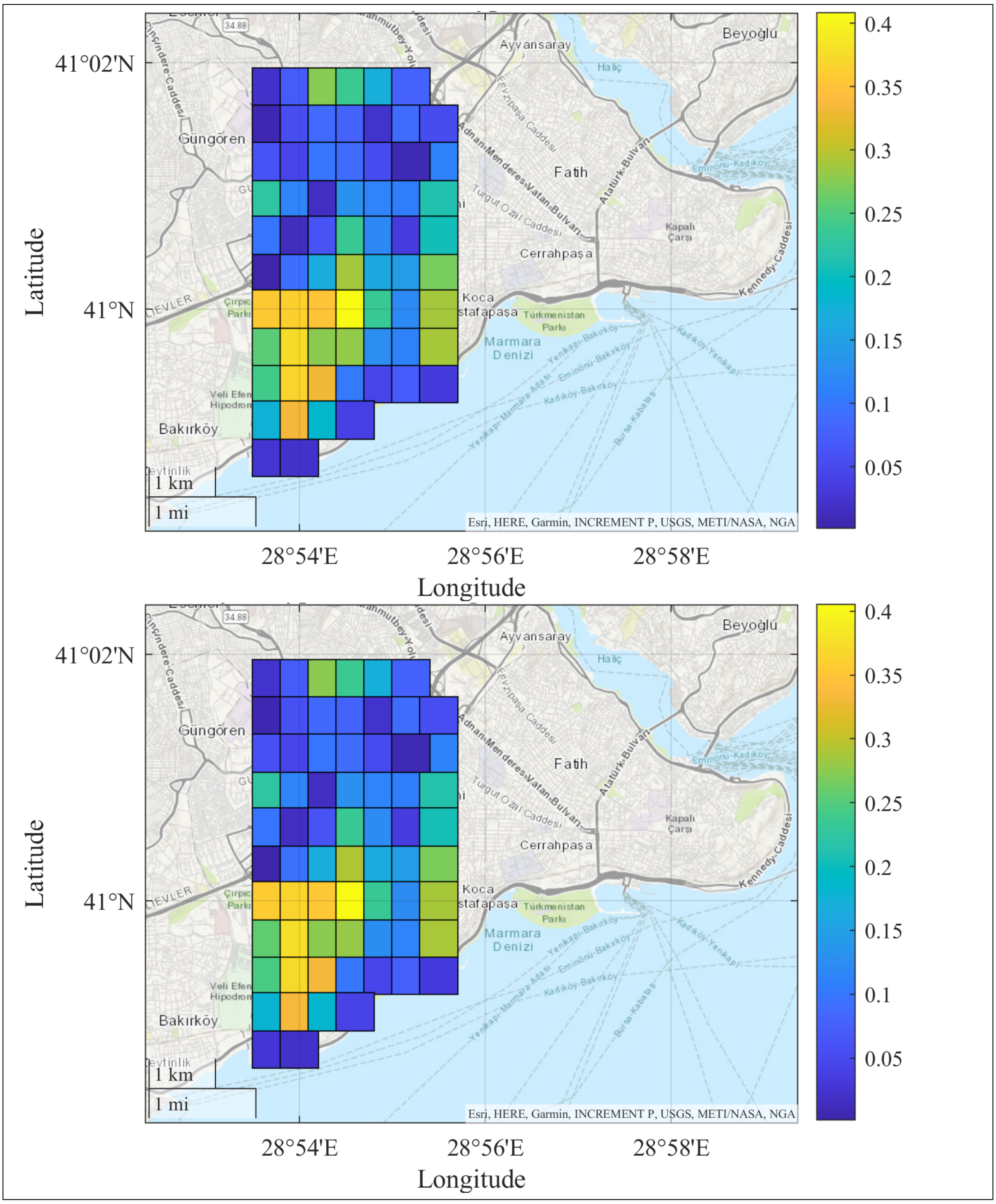
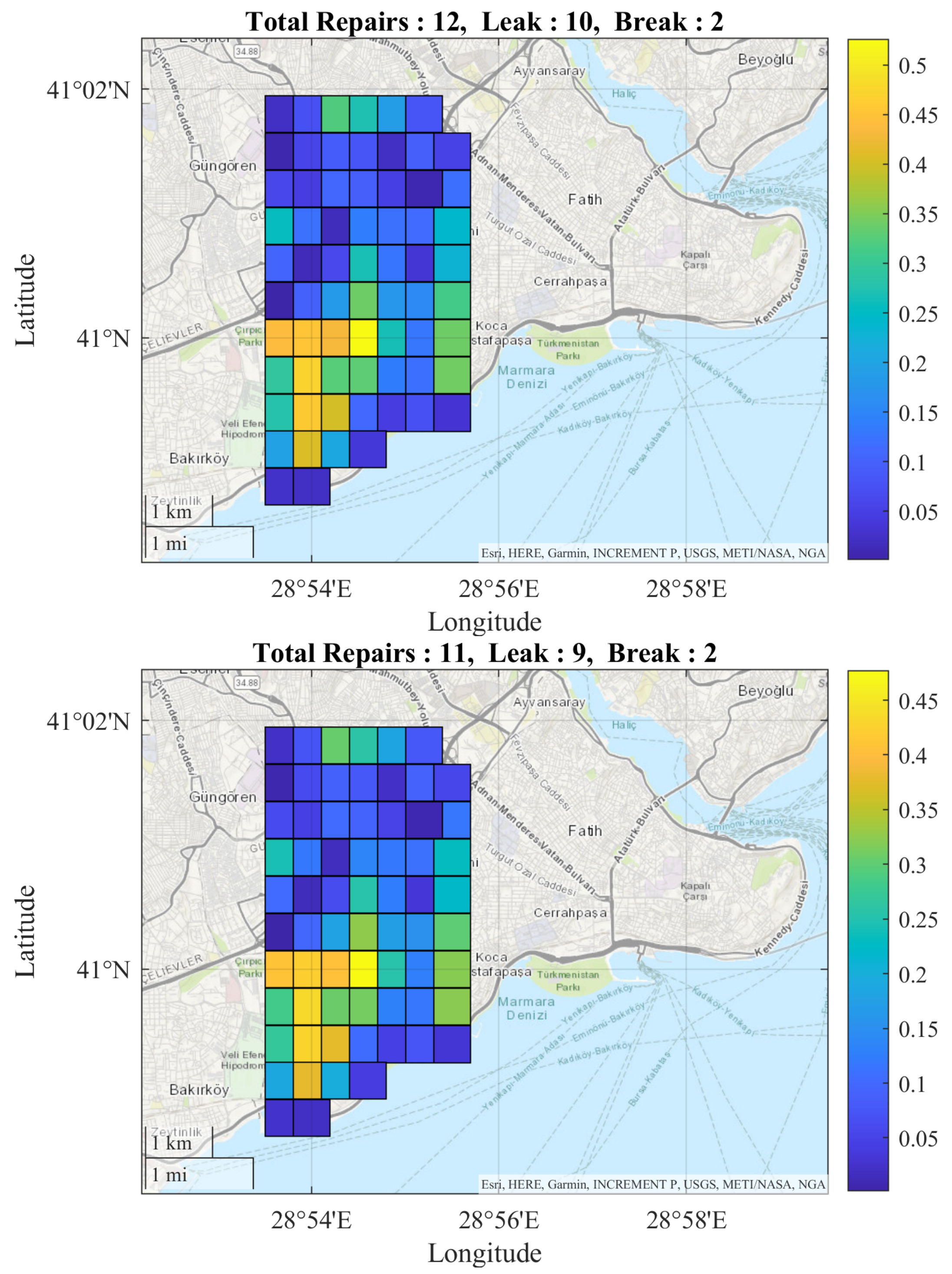


Figure 3.21. Maps of the probability of damage for bellmouth concrete pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).


Total Repairs : 12, Leak : 10, Break : 2

Total Repairs : 11, Leak : 9, Break : 2

Figure 3.22. Maps of the number of repairs for bellmouth concrete pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

3.3.3. Steel Pipes

For steel pipes, both of the approaches by ALA and ALA through Monte Carlo simulation do not yield any failures, because the multiplier for steel pipes in the formula suggested by ALA, 0.004, is very small. Since we round the results, any results close to zero are rounded to zero.

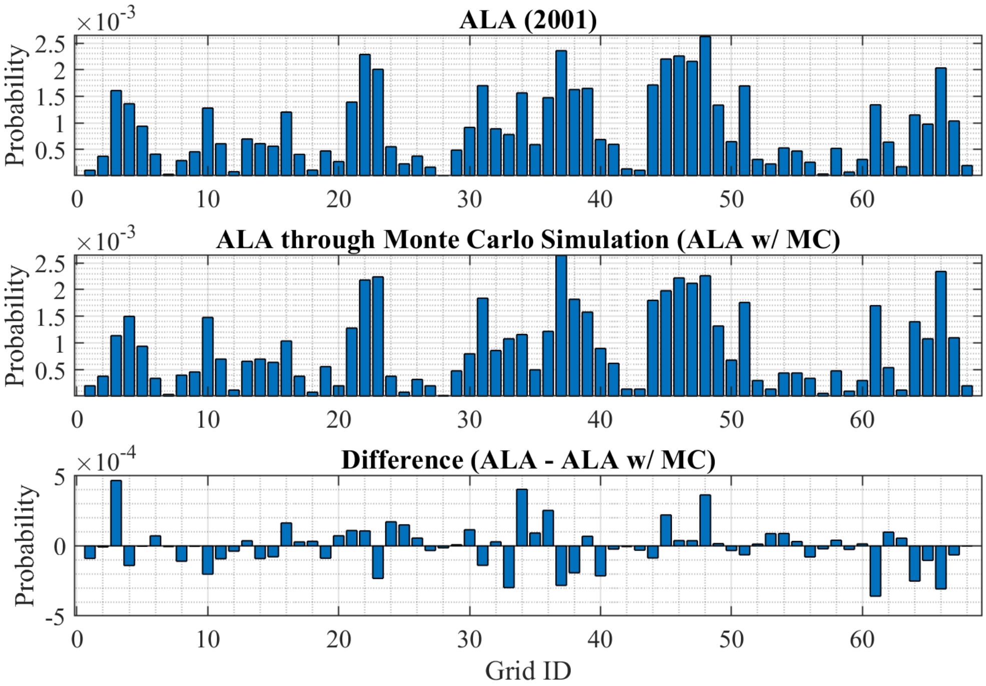


Figure 3.23. The probability of damage for steel pipes. The bottom figure shows the difference between damage probabilities calculated by using ALA and ALA through Monte Carlo simulation approaches.

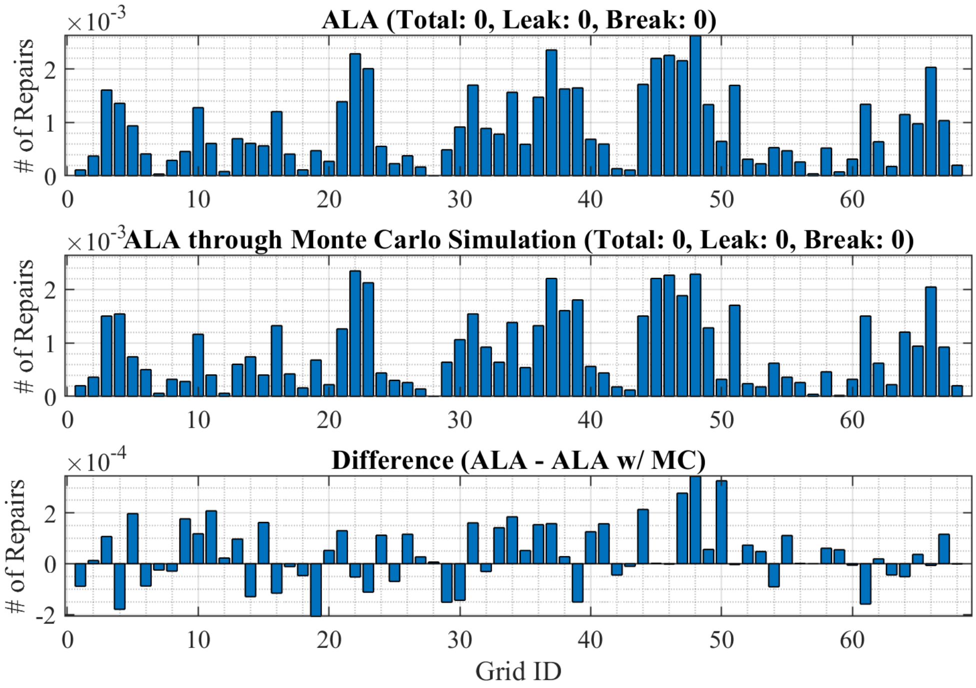


Figure 3.24. Number of repairs (leak + break) for steel pipes. The bottom figure shows the difference between number of repairs calculated by using ALA and ALA through Monte Carlo simulation approaches.

Geographical plots in Figure 3.25 and Figure 3.26 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

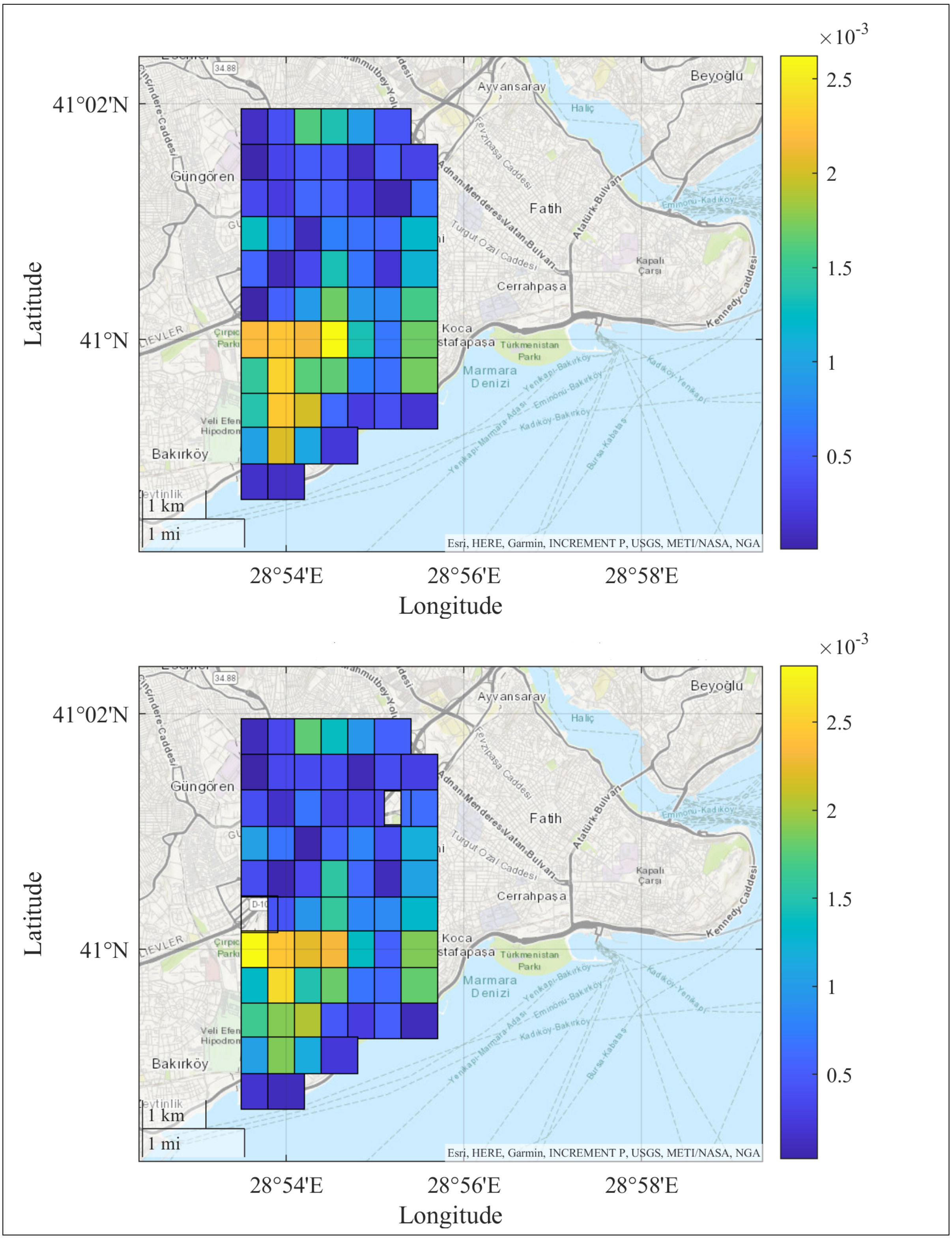


Figure 3.25. Maps of the probability of damage for steel pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

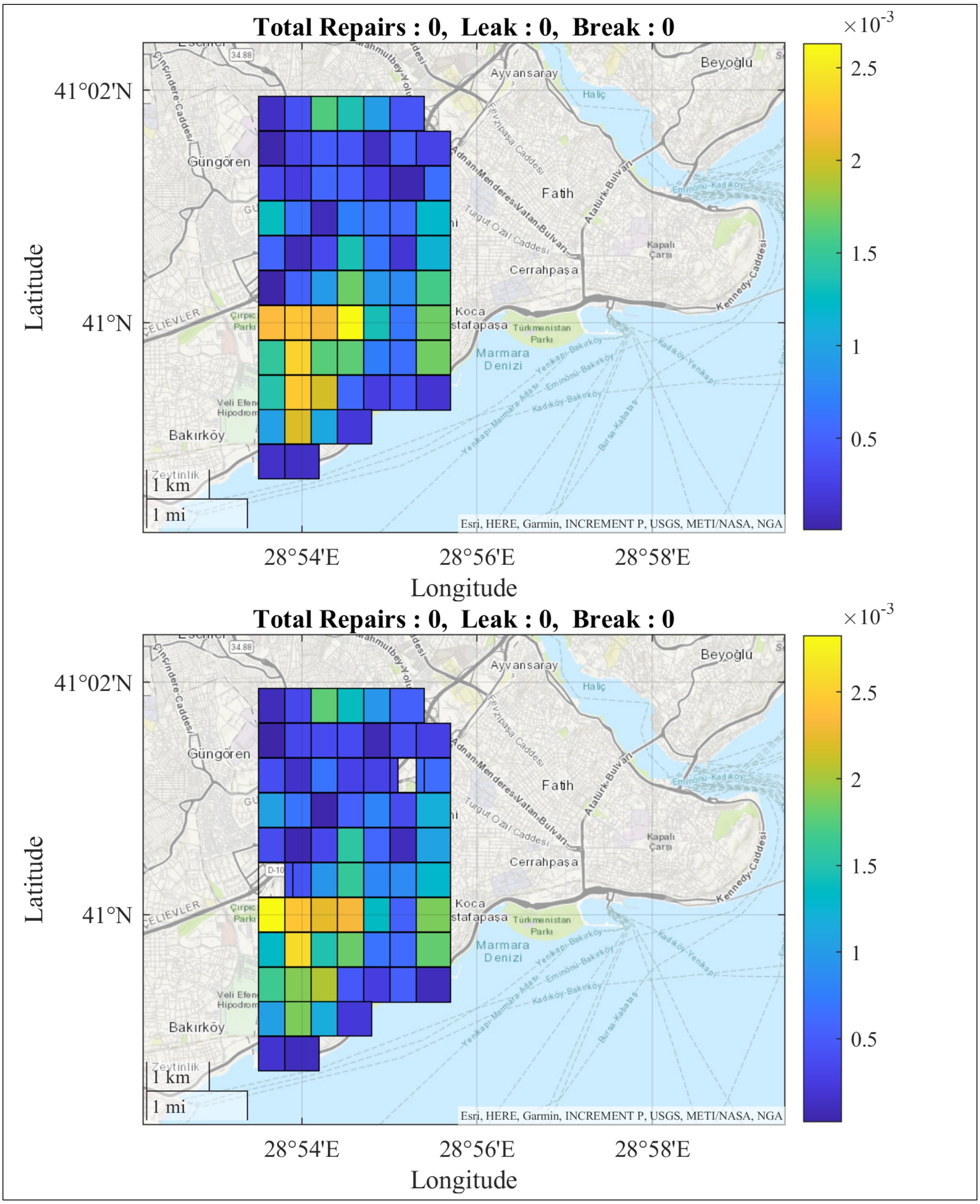


Figure 3.26. Maps of the number of repairs for steel pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

3.3.4. Polyethylene Pipes

For polyethylene pipes, using the algorithm suggested by ALA yielded 3 leaks and 1 break, whereas applying Monte Carlo simulation resulted in 4 leaks and 1 break. Among all the pipe and method combinations examined in this study, it is the first time that results for the leak by applying Monte Carlo sampling is bigger than the results without Monte Carlo sampling. This is because that the multiplier for polyethylene pipes is too small which results in more random numbers in the failure side when applying Monte Carlo simulation. In other words, after some certain points, reducing the multiplier yields more failures while performing Monte Carlo simulation.

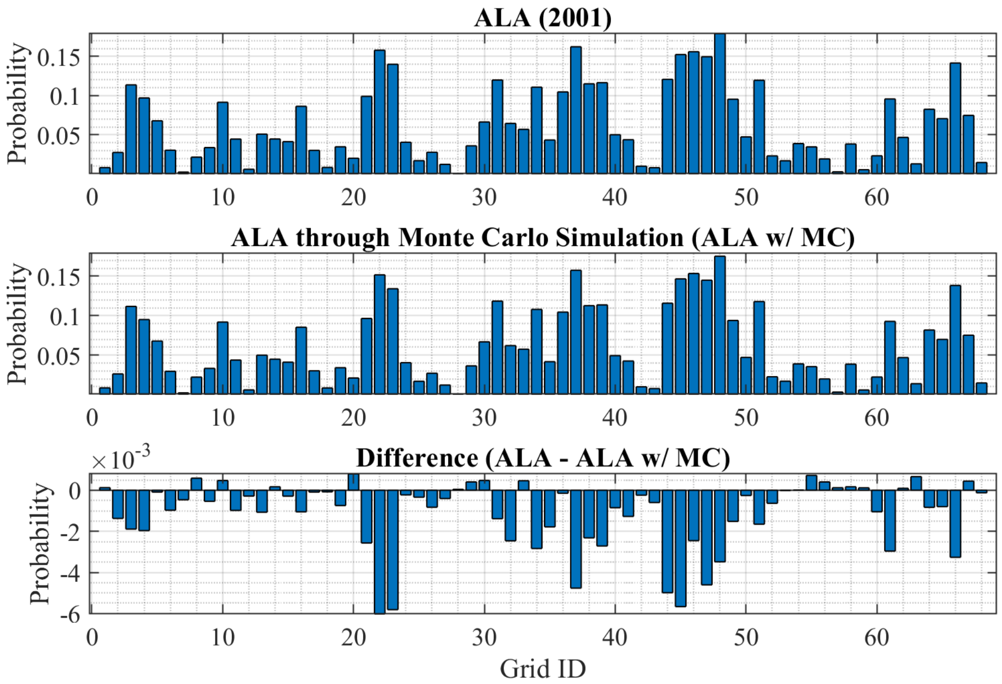


Figure 3.27. The probability of damage for polyethylene pipes. The bottom figure shows the difference between damage probabilities calculated by using ALA and ALA through Monte Carlo simulation approaches.

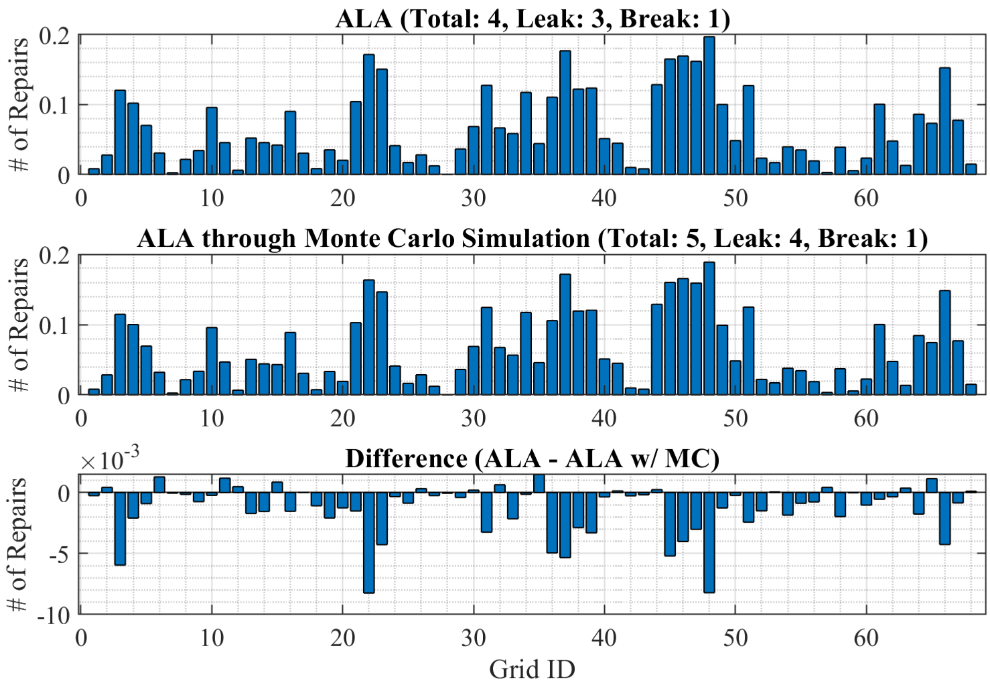


Figure 3.28. Number of repairs (leak + break) for polyethylene pipes. The bottom figure shows the difference between number of repairs calculated by using ALA and ALA through Monte Carlo simulation approaches.

Geographical plots in Figure 3.29 and Figure 3.30 are also developed to show the distribution of failure probabilities and repair numbers over the region studied for the material types of interest.

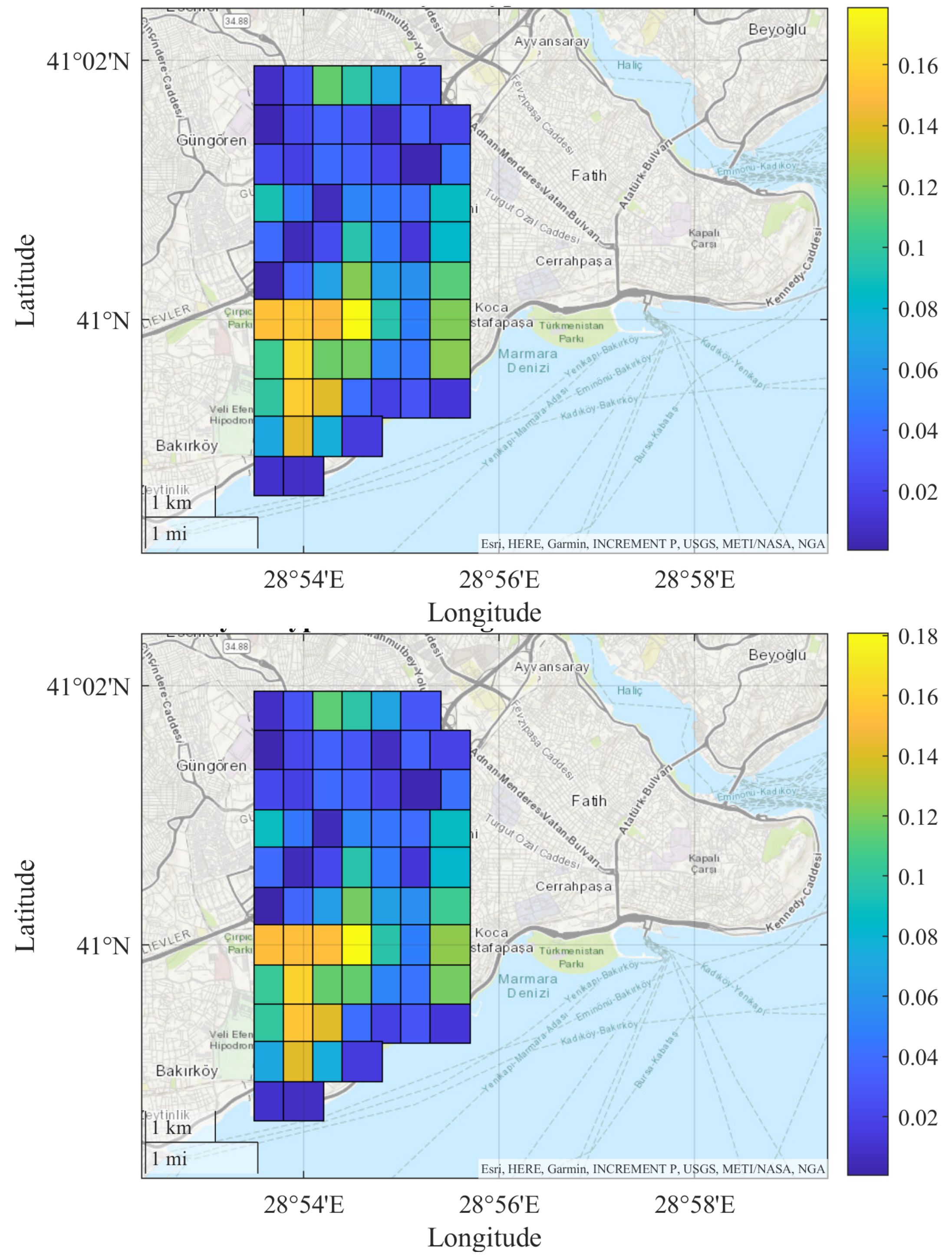
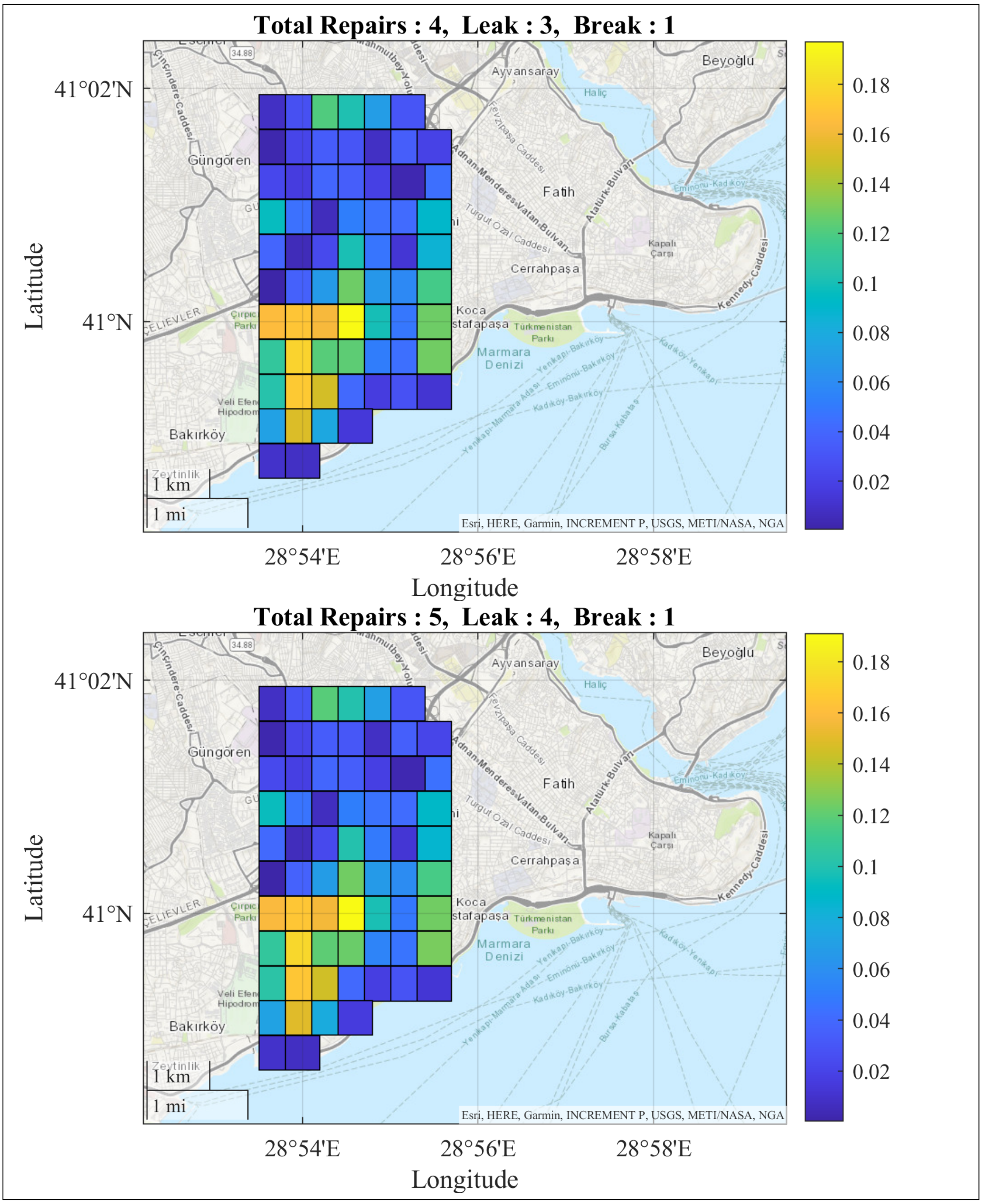


Figure 3.29. Maps of the probability of damage for polyethylene pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).



Total Repairs : 4, Leak : 3, Break : 1

Total Repairs : 5, Leak : 4, Break : 1

Esri, HERE, Garmin, INCREMENT P, USGS, METI/NASA, NGA

Figure 3.30. Maps of the number of repairs for polyethylene pipes calculated by ALA (top) and ALA through Monte Carlo simulation approaches (bottom).

3.4. Sensitivity Analysis

In Monte Carlo simulation, the number of samples is critical for the accuracy of the results obtained. To demonstrate this, we conduct a sensitivity analysis using HAZUS-FEMA and ALA approaches through the Monte Carlo simulation for the concrete and polyethylene pipes, respectively. We conduct the analyses for different sample numbers starting from 1 to 100,000 with increments of 100, and we plot the sample number versus the total number of repairs (leak + break). As can be seen from Figures 3.31 and 3.32, the results are highly dependent on the sample number for the small sample numbers and the results fluctuate a lot. However, with the increase in sample number, the results get close to each other and at some certain points, the changes in results differ only slightly. Figures 3.31 and 3.32 show that the 50,000 sample number is sufficient to apply the Monte Carlo simulation.

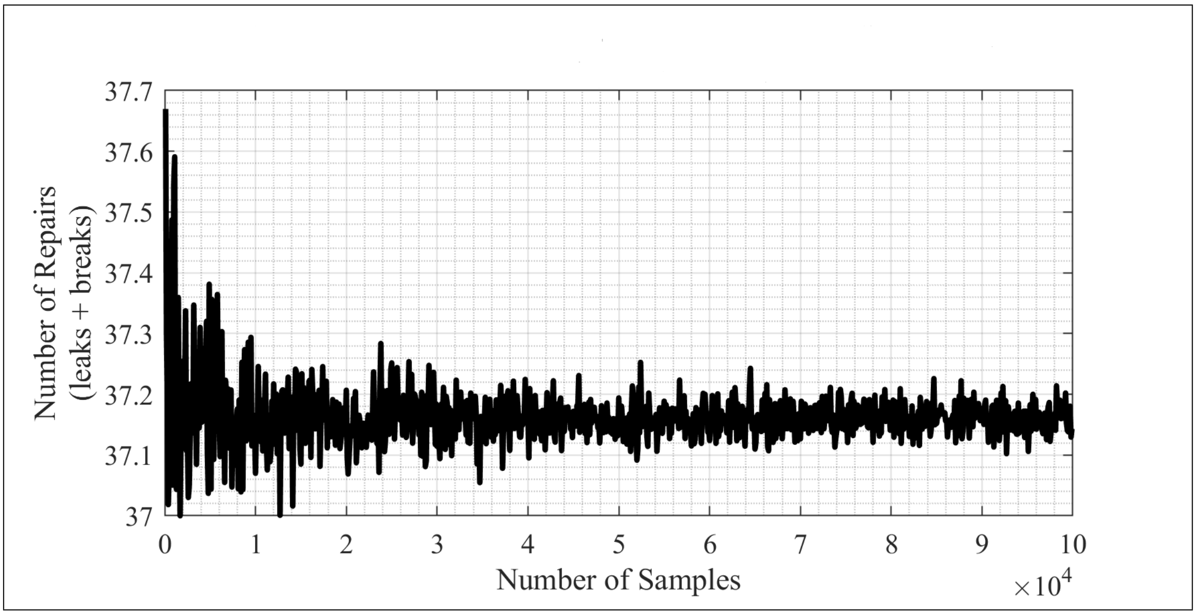


Figure 3.31. Sensitivity analysis for Monte Carlo simulation (analysis type: HAZUS through Monte Carlo simulation, material type: concrete).

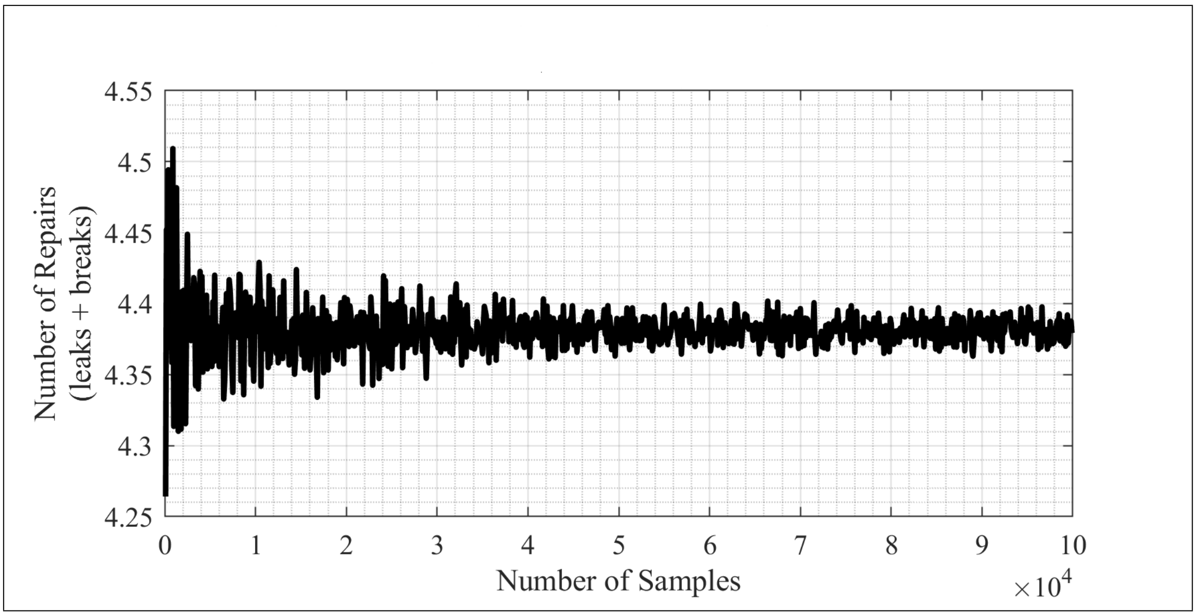


Figure 3.32. Sensitivity analysis for Monte Carlo simulation (analysis type: ALA through Monte Carlo simulation, material type: polyethylene).

4. RESULTS AND DISCUSSION

In this study, the damage assessment of a pipeline system in the Zeytinburnu location is performed for four types of materials by using the algorithms suggested by HAZUS-FEMA (2003) and American Lifeline Alliance (ALA-2001) under a scenario earthquake generated by ELER software. Also, the Monte Carlo simulation technique is incorporated into the analyses to reduce the uncertainties. To see the differences between the analysis types and material types, the results are compared conveniently in Figures 4.1 to 4.5.

The results show that the brittle materials (concrete and bellmouth concrete) are more vulnerable to earthquakes than ductile materials (steel and polyethylene). Moreover, applying Monte Carlo simulation generally yields smaller results in terms of repair numbers and failure probabilities.

Regarding the comparison of the two methods of HAZUS and ALA, the repair numbers from ALA are smaller than those from HAZUS for both leak and break numbers. In addition, the incorporation of the Monte Carlo simulation technique into the method by HAZUS reduces the number of repairs for all material types.

Concerning the material types, for concrete and bellmouth concrete, compared to the results in HAZUS-FEMA, the results of ALA are distinctly smaller. Moreover, applying Monte Carlo simulation changes the results slightly. For steel pipes, in ALA and ALA through Monte Carlo simulation, any failures are not observed due to the very small material coefficient (0.004). Only for polyethylene pipes, the results for the leaks by ALA through Monte Carlo simulation are bigger than the results of ALA. This is because that the multiplier for polyethylene pipes is too small which results in more random numbers in the failure side when applying Monte Carlo simulation. In other words, after some certain points, reducing the multiplier yields more failures while performing Monte Carlo simulation.

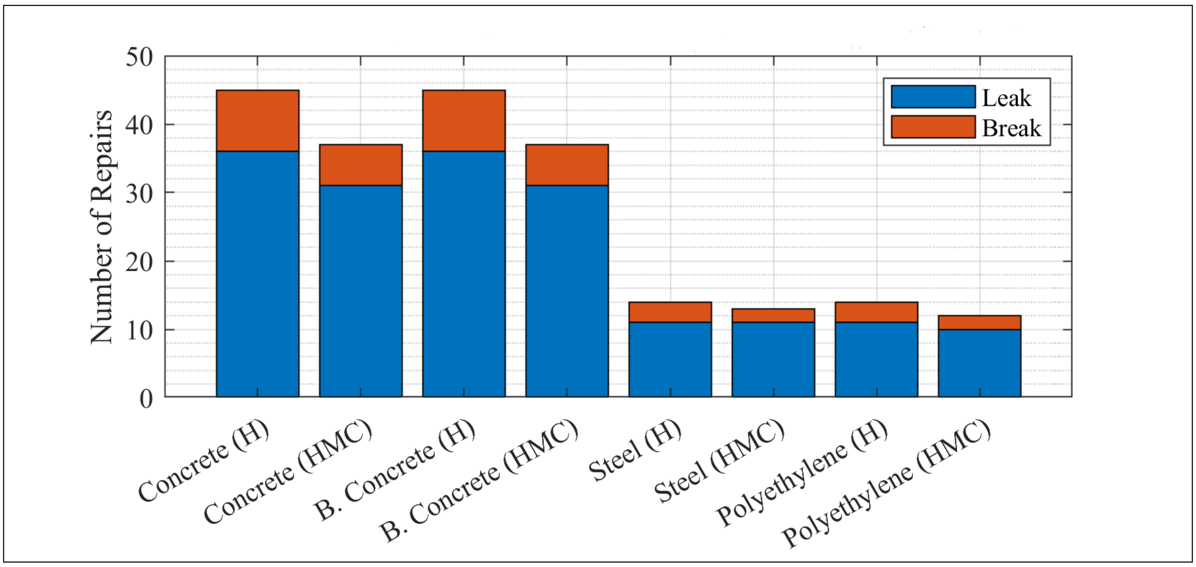


Figure 4.1. Comparison of the number of repairs calculated from HAZUS (H) and HAZUS through Monte Carlo simulation (HMC) approaches.

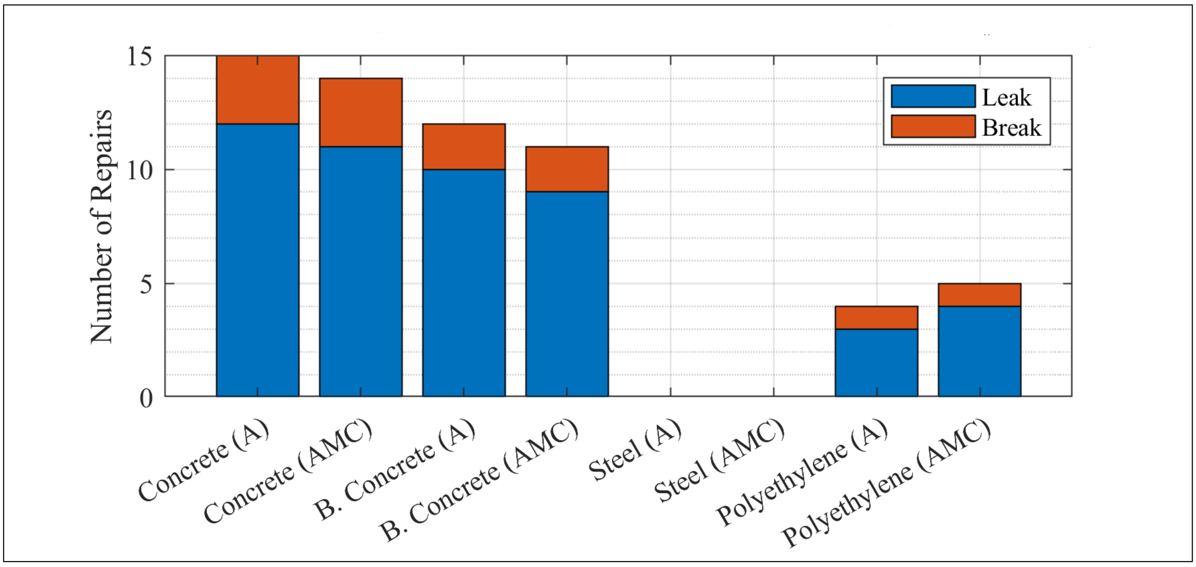


Figure 4.2. Comparison of the number of repairs calculated from ALA (A) and ALA through Monte Carlo simulation (AMC) approaches.

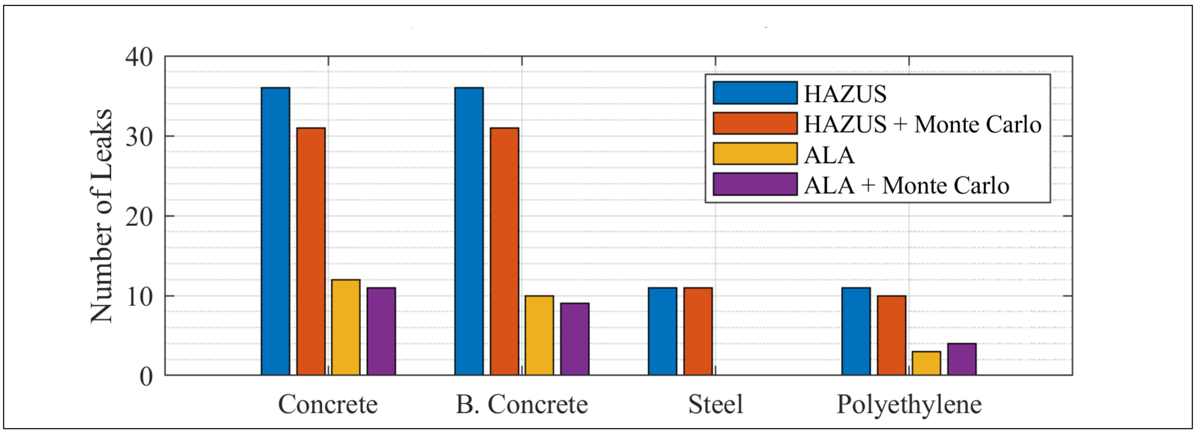


Figure 4.3. Comparison of the number of leaks of the pipes for all analysis and material types.

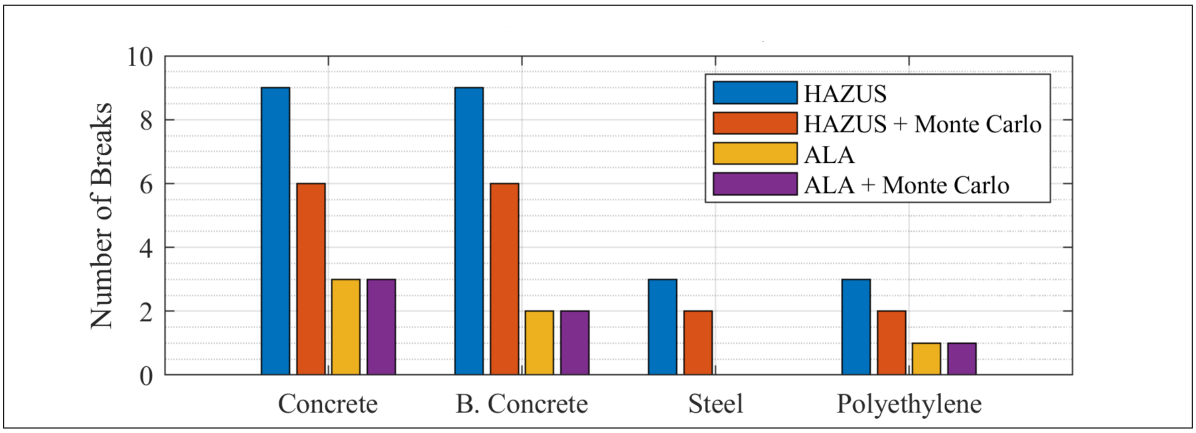


Figure 4.4. Comparison of the number of breaks of the pipes for all analysis and material types.

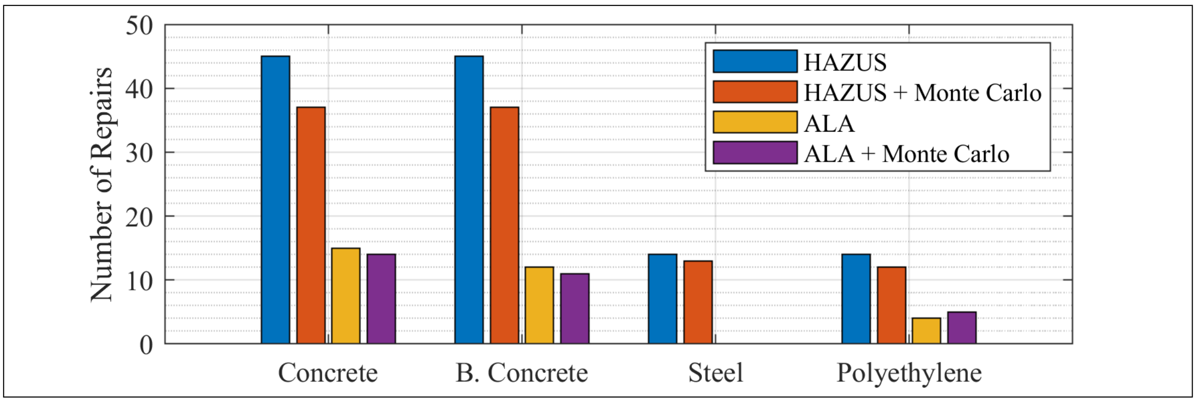


Figure 4.5. Comparison of the number of repairs (leaks + breaks) of the pipes for all analysis and material types.

5. CONCLUSION

In this study, algorithms suggested by both HAZUS-FEMA and American Lifeline Alliance (ALA) to predict the number of damages on the water pipeline system due to an earthquake are compared. Moreover, the Monte Carlo simulation technique is incorporated into these algorithms. Outcomes of this study show that the approach by HAZUS-FEMA yields bigger repair numbers than ALA does.

In HAZUS-FEMA approach, applying Monte Carlo Simulation clearly reduces the repair numbers for brittle materials. On the other hand, implementing Monte Carlo simulation to the HAZUS-FEMA algorithm only creates slight differences in repair numbers for ductile materials.

In ALA approach, applying Monte Carlo simulation only makes small differences for brittle materials. For steel pipes from ductile materials, any failures are not observed in neither ALA method nor ALA through Monte Carlo simulation. Moreover, the leak number of the polyethylene pipes is found slightly bigger when applying Monte Carlo simulation.

In this study, pipeline failures due to only one earthquake are calculated. Hence studying pipeline failures due to the earthquakes considered with a probabilistic approach will yield different PGV values. In this case, the repair rates will naturally change. To reach more reliable results, different earthquakes with different magnitudes should be taken into consideration in the future studies. In addition, considering only four different material types is another limitation in this study. Expanding the study with different material types and different diameters will undeniably make great contributions to the study of pipeline damages. Concerning the grid sizes, this study is performed only for one grid type which is 420m by 555m. Since changing the grid size changes the pipeline length in a grid, the results will also be different. Hence, the effects of different grid sizes on pipeline damages should be taken into consideration in the future studies.

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