

Risk Prediction Model for Formation of Underground Cavities and Sinkholes due to Defective Sewer Pipes

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ABSTRACT

Sinkhole formation due to internal erosion around defective sewer pipes is identified as a serious threat in urban infrastructure system. Post-repair and rehabilitation after pipe failure are not effective as emergency pipe repairs are very costly and pipe failure leads to various public and environmental consequences. Only a few studies have been conducted on the prediction of the risk of ground erosion around pipe defects. Therefore, the main objective of this article is to propose a model which can predict the risk of formation of sinkholes around sewer pipelines based on the weighted factors method when a pipe defect is certain. The proposed methodology relies on different factors which contribute to void development and severity of the consequences. The Risk of Erosion (ROE) combines the effect of Likelihood of Erosion void formation (LOE) and Consequence of Erosion cavity formation and ground failure (COE). The LOE rating is related to many parameters, including soil properties, hydraulic conditions, and pipe defect characteristics, while the COE rating is related to the environmental, economic, and social consequences of pipe failure. Therefore, this model, which can predict the risk of developing a sinkhole close to an existing pipe defect, will enable sewer assets maintenance teams to evaluate each pipe and prioritize the maintenance and rehabilitation work based on the risk to each pipe.

Keywords: Sinkholes, Risk Prediction Model, Sewer Rehabilitation, Internal Erosion

1 INTRODUCTION

Wastewater and stormwater collection systems are critical components of urban infrastructure systems in any country. Failure of deteriorated buried sewer pipes can occur in two ways. One process is when the soil backfill in the vicinity of a pipe defect is gradually eroded, the pipe will bend and collapse due to loss of confinement from the ground (Balkaya et al. 2012). The second process occurs when the cracks are formed at either sides or the crown of the pipe. Voids can develop above the pipe while the pipe is still well supported from the bottom. In this case, erosion may propagate towards the ground surface causing a sinkhole which eventually breaks most of the other buried service lines (Sato and Kuwano 2015).

Many studies have been conducted on sewer deterioration and risk prediction models for pipe failures (Yan and Vairavamoorthy 2003; Baah et al. 2015; Emilio 2015). To the author's best knowledge, only one risk prediction model is available in the literature (Kaddoura and Zayed 2017) which proposed a model that can predict the risk of void erosion present outside sewer pipelines. This is based on weighted factors method using Fuzzy theory. However, this model has several limitations. It does not account for a few other critical factors which control the process of cavity formation such as the relative density or compaction of the ground and the influence of rainfall. Moreover, the erosion susceptibility of clay has been considered as higher than fine sand and silt which is contradicting with available literature (Rogers 1986, Indiketiya 2019). The model only predicts the probability of erosion void presence outside sewer pipes and the risk due to consequences of erosion void formation is not accounted for the overall risk.

Therefore, it will be useful to develop an efficient model which can predict the overall risk of developing erosion voids in defective sewers which can be useful to sewer assets management teams for allocating priorities in

rehabilitation projects and for sewer and storm water pipe designers to design high stability backfill design considering the erosion resistance of the backfill.

2 METHODOLOGY

2.1 Risk assessment method

Most of the risk assessments conducted for sewer failures as outlined in available literature have considered some form of likelihood or probability of failure, consequence of failure and risk of failure. Emilio (2015) adopted a similar method to predict the risk of failure of sewer pipes. Therefore, modified version of the same approach is used in this study to predict the risk of erosion void formation (ROE) which combines the likelihood of erosion void formation (LOE) and consequence of erosion void formation (COE) in sewer pipes. The risk assessment involved identifying influencing parameters for LOE and COE then quantifying the LOE and COE by assigning critical scores based on the literature and by allocating factor weights based on experts' opinion. After both ratings were determined, they were multiplied together to find the risk score for ROE as shown in Equation 1.

$$\text{ROE} = \text{LOE} * \text{COE} \quad (1)$$

Following an extensive literature review, seven most influencing parameters which control the erosion initiation and progression through pipe defects were identified for the LOE function as shown in Equation 2. The contribution from each factor to LOE, λ_i was estimated based on the expert's belief where, each $0 \leq \lambda_i \leq 1$ and $\sum \lambda_i = 1$.

$$\text{LOE} = \lambda_1. \text{Soil type score} + \lambda_2. \text{Relative density of backfill score} + \lambda_3. \text{Depth of sewer pipe score} + \lambda_4. \text{Location of GWT score} + \lambda_5. \text{Pipe defect size score} + \lambda_6. \text{Frequency and magnitude of sewer exfiltration score} + \lambda_7. \text{Frequency and magnitude of rainfall score} \quad (2)$$

The consequences of the erosion void formation and sinkhole formation are very similar to the consequences of the pipe failures. Therefore, four parameters which have been commonly adopted in previous risk prediction models for pipe deterioration (Baah et al. 2015; Emilio 2015) were selected for COE of this model. Selected four factors to represent environmental, economic, and social impacts of the pipe location are depicted in Equation 3. Where, μ_i was estimated based on the expert's belief while satisfying $0 \leq \mu_i \leq 1$ and $\sum \mu_i = 1$.

$$\text{COE} = \mu_1 \cdot \text{Environmental-pipe diameter score} + \mu_2 \cdot \text{Economic-commercial zone score} + \mu_3 \cdot \text{Social-critical infrastructure score} + \mu_4 \cdot \text{Social-traffic volume score} \quad (3)$$

2.2 Assigning critically scores for LOE

The condition of each pipe is evaluated for the LOE based on seven factors and each parameter was assessed and scored between 0 and 4 as given in Table 1 to Table 7. Therefore, the overall risk of LOE of pipe will also be scored out of 4 as $0 \leq \lambda_i \leq 1$ and $\sum \lambda_i = 1$, as depicted in Equation 2. The scoring criteria for each of the seven factors are summarized through section 2.2.1 to 2.2.7.

2.2.1 Soil Characteristics

The soil type, its particle-size distribution and plasticity are identified as key parameters which controls the initiation of erosion through pipe cracks (Rogers 1986; Sato and Kuwano 2015; Indiketiya 2019). Considering all those data, soil types were arranged into a hierarchy based on the erosion resistance through underground openings and tabulated as shown in Table 1.

Table 1. Scoring for soil type

Soil type (USCS specification)	Attribute	Score
GW, GC, CH	Excellent	0
CL-CH, SC, GM	Good	1
SW, CL, GP	Fair	2
SM, CL-ML, MH	Poor	3
SM, ML, SP, Dispersive Clay	Worst	4

2.2.2 Relative density of the backfill

The importance of having a higher relative density to minimise erosion potential in non-cohesive material has also been discussed by Rogers (1986) and Renuka (2012). Most of the sewer pipe construction specifications have recommended minimum compaction of 70% relative density for pipe embedment (United States Department of the Interior 1996; WSA 02-2002-2.3-MRWA Edition 2002). Therefore, considering the experimental results from above researchers, different scores were assigned to each pipe backfill density as displayed in Table 2.

Table 2. Scoring for density of backfill

Relative density (Non-Cohesive Soil)	Attribute	Score
>90%	Excellent	0
70%-90%	Good	1
60-70%	Fair	2
35-60%	Poor	3
<35%	Worst	4

2.2.3 The depth of the sewer

Pipes which are closer to ground surface are often disturbed and damaged due to heavy traffic, construction works and maintenance of other underground services (Davies et al. 2001). In addition, O'Reilly et al. (1989) found out that the defect rate decreases with the increasing of the pipeline depth. The chance of erosion initiation and propagation also could increase at a lower depth due to lower confining pressure and faster rain infiltration through the opening. Kaddoura and Zayed (2017), also proposed a depth categorisation for sewer pipes in his void erosion prediction model. Based on the above-mentioned discussion and studies, pipes are scored based on its depth in LOE function as displayed in the Table 3.

Table 3. Scoring for depth of the pipeline

The depth of the sewer (m)	Attribute	Score
> 4	Excellent	0
2-4	Good	1
1.2-2	Fair	2
0.6-1.2	Poor	3
0-0.6	Worst	4

2.2.4 Location of the GWT

If the GWL exists above the sewer pipeline or above any structural defect, there is a higher possibility of infiltration and soil migrating to the sewer pipeline (Davies et al. 2001). Indiketiya (2019) also discussed propagation of erosion voids considering the geometry of the void and the relative location of the GWT. Similar studies have categorised the influence of GWT into two as pipe located above and below the GWT (Rogers 1986; Davies et al. 2001). However, the most important fact is the location of the GWT relative to the pipe defect. As crack or the opening in a pipe can be at the bottom or the crown, choosing the depth of pipe can be misleading for large diameter pipes. Therefore, in this model, sewer depth was categorised and scored into three sections as shown in Table 4.

Table 4. Criticality scoring for the GWT

Groundwater table	Attribute	Score
Well below the pipeline	Excellent	0
Closer to the pipeline	Poor	3
Above the pipeline	Worst	4

2.2.5 Effect of pipe defect size

Pipe defect size is one of the most governing factors which controls the rate of soil loss. Rogers (1986) first proposed a relationship between ground loss and the ratio of B/D_{85} for a variety of cohesionless soils under the one-way water flow. Where D_{85} is the size of sieve through which 85% by weight of a soil sample will pass and "B" is the crack width. Critical crack width for continuous migration of soil in monotonic water flow was expressed as $2.5D_{85}$ to $4.5D_{85}$. Indiketiya (2019) observed that the rate of soil loss is significantly smaller if the "B" is less than D_{max} or $2D_{85}$ of the backfill material and soil loss was critical when "B" was greater than $2D_{max}$. These findings are consistent with the studies available on granular flow through orifices. Based on these findings, pipe defects were categorised into different groups for critical scoring as given in Table 5.

Table 5. Criticality scoring for the pipe defect

B/D _{max}	B/D ₈₅	Attribute	Score
<0.75	<1	Excellent	0
0.75-1	1-2	Fair	2
1-2	2-3	Poor	3
>2	>3	Worst	4

2.2.6 The magnitude of sewer exfiltration

Rogers (1986) performed a series of physical model tests to examine the soil loss from sewer exfiltration from pipe and groundwater infiltration into the pipe. It was revealed that in fine-granular soil, the frequency of sewer exfiltration or leakages with a smaller surcharge was more critical than having a single leakage with a larger surcharge. Therefore, even minor daily leakages through the pipe cracks can cause significant soil loss if the flow occurs cyclically through large defects. The hierarchy proposed in WRC (2001) for the magnitude and frequency of sewer leakages is used in this model by assigning criticality scores as shown in Table 6.

Table 6. Scoring for sewer exfiltration

The magnitude of exfiltration	Attribute	Score
Never	Excellent	0
Occasional, low magnitude	Good	1
Occasional, high magnitude	Fair	2
Frequent, lower magnitude	Poor	3
Frequent, high magnitude	Worst	4

2.2.7 The magnitude of rainfall

Kuwano et al. (2006) reported that majority of sinkholes in Japan are formed in the rainy season. Rise in GWT, frequent sewer overflows, and groundwater infiltration through existing cavities due to rain can accelerate the erosion process and sinkhole development. Referring to the classification introduced by WRC (2001) for sewer exfiltration which was presented in Table 6, a very similar approach was used in this model to classify the frequency and magnitude of rainfall. It is difficult to quantify the magnitude and the frequency of rainfall for each group as it is sensitive to location and the country. Therefore, the proposed qualitative classification in Table 7 can be adapted to any location based on a relative judgment.

Table 7. Scoring for the magnitude of rainfall

The magnitude of rainfall	Attribute	Score
No rainfall	Excellent	0
Occasional, light shower	Good	1
Frequent, light shower	Fair	2
Occasional, heavy rainfall	Poor	3
Frequent, heavy rainfall	Worst	4

2.3 Assigning critically scores for COE

The COE is a representation of values of financial or of life-loss, and it measures the effect of pipe failure regarding environmental, economic, and social consequences. There are various studies which predict the risk of consequences of pipe failures. Erosion void formation and ground subsidence have very similar consequences regarding environmental, social and economic impacts. Therefore, the four parameters used by Emilio (2015) for sewer pipe failures are used in this model.

The parameters include pipe diameter, distance from commercial zones, distance from critical infrastructure, and vehicular traffic volume as parameters for quantifying the environmental, economic, and social consequences. The scoring criteria for each of the four factors above are summarized below in Section 2.3.1 to 2.3.4.

Similar to LOE scoring, COE scoring is assigned under six attributes as excellent, very good, good, fair, poor and worst. The scores are assigned as 0, 1, 2, 3, 4, 5 respectively. Therefore, the overall risk of COE of erosion void formation closer to a pipe is scored out of 5 as $0 \leq \mu_i \leq 1$ and $\sum \mu_i = 1$.

2.3.1 The size of the pipe diameter

Pipe diameter is a crucial factor in COE function as it represents the volume of sewer flow, the amount of public coverage and the potential environmental consequences in a sinkhole event or rehabilitation work. For large diameter pipes, pipes cover a larger domestic and industrial buildings and if a pipe breaks the public inconvenience is higher. When the diameter is increased, the depth of the pipe is also higher, and the consequences of sinkhole formation will be greater as the size of the sinkhole is increasing with the depth (Guo et al. 2013). Therefore, the total cost, effort and time required for a repair are higher than in a smaller size pipe. Table 8 shows the scoring breakdown for the pipe diameter. This categorisation is referring Emilio (2015) and actual sewer pipe sizes available in real practice in Australia.

Table 8. Scoring for the size of the pipe diameter

Pipe Diameter (mm)	Attribute	Score
<150	Excellent	0
180 - 225	Very Good	1
250 - 375	Good	2
400 - 525	Fair	3
550-750	Poor	4
>750	Worst	5

2.3.2 The distance from commercial zones

In Australia, different states use different land zone classifications and Victoria's major zonings are residential, commercial, industrial and rural, in addition to sub-zones as specified by the State Government of Victoria (2014). In commercial zones, there are commercial activities which are essential for functioning of a city such as retail shops, offices and childcare centres. Therefore, the distance from the sinkhole to these commercial zones is important, the greater the distance, the lower the risk of consequences. Scores defined by Emilio (2015) are selected for this model as shown in Table 9. Based on the scoring, pipes which are 1500m away from commercial activities have less impact while those located closer than 300m have severe impact.

Table 9. Scoring for the distance from commercial zones

Distance from commercial zones (m)	Attribute	Score
>1500	Excellent	0
1200 - 1500	Very Good	1
900 - 1200	Good	2
900 - 600	Fair	3
300-600	Poor	4
<300	Worst	5

2.3.3 The distance from critical infrastructure

Critical infrastructure enables the provision of essential services such as food, water, health, energy, communications, transportation, emergency services and banking. Sinkholes, pipe breaks and the subsequent repairs may influence a city’s ability to respond to emergencies. Emilio (2015) also counted schools as critical infrastructure in his model, as schools are large public gathering points that may be negatively affected. The same scoring breakdown used by Emilio (2015) is applied in this COE model as shown in Table 10 since pipe failures have very similar consequences to sinkhole events.

Table 10. Scoring for the distance from critical infrastructure

Distance from critical infrastructure (m)	Attribute	Score
>2500	Excellent	0
2499 - 2000	Very Good	1
1999 - 1500	Good	2
1499 - 1000	Fair	3
999-500	Poor	4
<500	Worst	5

2.3.4 The traffic volume/road type of the location

The type of the road or the volume of traffic where the sinkhole appears are crucial which affect the consequences of the event. However, as the traffic volume highly depends on the location, the city and the country, it is difficult to normalise the volume of traffic as an indicator for general practice. Therefore, road type would be beneficial as it is a relative gauge which can be easily replaced for different countries. There is a variety of classifications for road types, and no single variable is available to completely describe a class of roads. The road classification implemented throughout Victoria according to (Austroads 2005) are used here. According to this hierarchy, “M” routes deserve a higher critical score as it carries the highest traffic volume and has greatest connectivity within the road network. The scoring system proposed in this study is given in Table 11. Footpaths are also added with the lowest critical score as some sewer pipes are buried in footpaths which are not included in the national road numbering system.

Table 11. Criticality scoring for the road type

Distance from critical infrastructure (m)	Attribute	Score
Footpaths	Very Good	1
C	Good	2
B	Fair	3
A	Poor	4
M	Worst	5

2.4 Data acquisition for weighted influence factors

Two of the recommended methods for estimating influence factors (λ and μ values) in Equation 2 and 3 is to get the expert’s judgment (Joseph et al. 2010) or iterative computation through field data (Emilio 2015; Kaddoura and Zayed 2017). As collecting actual field data related to defective sewer pipes and sinkhole events are extremely difficult, multiple experts are selected by considering the experience and confidence on the topic.

As this theme is still quite new and thorough knowledge about the pipe deterioration and erosion process is required to fill up the questionnaire, 15 researchers were selected from various countries referring to their publications which indicates their expertise on this study area. All the information required for survey was provided and experts were requested to assign λ_i and μ_i values corresponding to parameters from their expertise so that $\sum(\lambda_i) = 1$ for LOE and $\sum(\mu_i) = 1$ for COE separately.

2.5 Data analysis and determination of weighted influence factors

The proposed λ_i and μ_i values by experts were scattered in a wide range. Therefore, the weighted average (Mean) and the mode of each data set for λ_i and μ_i are calculated and presented in Table 12 and Table 13 respectively. The mean and the mode of all seven λ_i values are close and consistent. Therefore, final λ values were designed clearly as closely following the mean and the mode values while satisfying the condition of $\sum(\lambda_i) = 1$.

However, all four μ_i , parameters are having higher standard deviations while mean and the mode values are also slightly different. Therefore, considering the mean, mode and the distribution of the normal frequency, judgment on final value was decided as presented in Table 13. Emilio (2015) had the same parameters in the COE model and the judgment was $\mu_1=0.3$, $\mu_2=0.3$, $\mu_3=0.2$ and $\mu_4=0.2$. These have been decided manually based on judgment where more emphasis was applied to social concerns because they directly affect the public.

Therefore, the final equations for LOE and COE with the proposed influencing factors can be written as shown below in Equations 4 and 5.

Table 12 The Mean, mode and proposed λ_i values

Parameter	λ		
	Mean	Mode	Proposed
λ_1	0.19	0.2	0.2
λ_2	0.11	0.1	0.1
λ_3	0.09	0.1	0.1
λ_4	0.18	0.2	0.2
λ_5	0.21	0.2	0.2
λ_6	0.12	0.1	0.1
λ_7	0.10	0.1	0.1
$\sum(\lambda_i)$			1.0

Table 13 The Mean, mode and proposed μ_i values

Parameter	μ		
	Mean	Mode	Proposed
μ_1	0.26	0.3	0.3
μ_2	0.25	0.2	0.2
μ_3	0.25	0.3	0.25
μ_4	0.25	0.2	0.25
$\sum(\mu_i)$			1.0

$$\text{LOE} = 0.2 * (\text{Soil type score}) + 0.1 * (\text{Relative density of backfill score}) + 0.1 * (\text{Depth of sewer score}) + 0.2 * (\text{Location of GWT score}) + 0.2 * (\text{Effect of pipe defect size score}) + 0.1 * (\text{Frequency and magnitude of sewer exfiltration score}) + 0.1 * (\text{Frequency and magnitude of rainfall score}) \tag{4}$$

$$\text{COE} = 0.3 * (\text{Environmental-pipe diameter score}) + 0.2 * (\text{Economic-commercial zone score}) + 0.25 * (\text{Social-critical infrastructure score}) + 0.25 * (\text{Social-traffic volume score}) \tag{5}$$

Table 14. Risk level categorisation for ROE based on a risk matrix

Likelihood of erosion (LOE)	Consequences of erosion void formation (COE)					
	0 (Low)	1 (Low)	2 (Low to moderate)	3 (Moderate)	4 (High)	5 (Very high)
0 (Low)	0 Low	0 Low	0 Low	0 Low	0 Low	0 Low
1 (Low to moderate)	0 Low	1 Low	2 Low	3 Low	4 Low	5 Moderate
2 (Moderate)	0 Low	2 Low	4 Low	6 Moderate	8 Moderate	10 High
3 (High)	0 Low	3 Low	6 Moderate	9 Moderate	12 High	15 Very high
4 (Very high)	0 Low	4 Low	8 Moderate	12 High	16 Very high	20 Very high

Since the LOE is scored out of 4 and COE is scored out of 5, this model considers pipes with LOE of 3 to 4 as the higher vulnerability for ground subsidence with pipe failure and in need of urgent attention. Similarly, COE is scored out of 5 and pipes with COE score of 4 to 5 are considered as critical pipes which causes many social, economic and environmental consequences. Various studies have graphically illustrated the risk matrix system (Baah et al. 2015) which combines the probability and consequences for an event. Referring those studies, risk level for a pipe to develop an erosion cavity was categorised through the risk matrix based on the score as low, moderate, high and very high as illustrated with a colour code in Table 14.

3 VALIDATION

The model can be validated one of these methods: (1) comparison of the predicted risk with that of previous models, (2) validation based on real field data or (3) implementation of the model in a case study. Detailed reports of investigations of sinkhole accidents are extremely rare, as the relevant authority's primary goal is to restore the infrastructure as quickly as possible to minimise the public, economic and social inconvenience. General information about the events is usually published in media as news reports. All the attempts to access some field data to validate the model from local and international authorities were unsuccessful as the present research is a university-based study without any industrial collaborations.

The ROE model presented in this chapter was developed following a thorough study of previous research related to erosion through pipe defects, risk prediction models for pipe failures and the experimental investigations available in literature. The output of COE is closely aligned with Emilio 2015). Nevertheless, the LOE function needs to be validated before implementing it in industrial applications.

4 CONCLUSIONS

Based on the study, the following conclusions were driven.

- Seven key parameters which affect the likelihood of erosion void formation are identified. Of those parameters, the soil type, the size of the pipe defect

and the location of the GWT have the highest relative weights.

Four parameters which evaluates the consequences of erosion void formation were considered as the pipe diameter, the distance from commercial zone, the distance from critical infrastructure and the road type of the location

- Criticality scores for LOE function was scored out of 4 and COE function was scored out of 5. Therefore, the overall risk of erosion, ROE is predicted rating out of 20. Then the level of risk for a defective pipe to develop an erosion cavity is categorised according to a risk matrix based on the ROE score: low (0 to 4), moderate (5 to 9), high (10 to 14) and very high (15 to 20).
- Unfortunately, due to lack of published data, and the legal requirements of different institutes and countries, it proved impossible to access real data to validate the model. However, this model development contributes significantly to existing knowledge. Therefore, it can be validated and improved with collaboration from industry partners in a future study.
- Ultimately, this allows defective pipes to be ranked based on the risk of erosion void formation and consequences which assist to organise a maintenance and rehabilitation schedule by allocating the priority.

5 ACKNOWLEDGEMENTS

Authors would like to acknowledge:

- Swinburne University of Technology in supporting this research by offering Swinburne University Postgraduate Research Award.
- All the research experts who contributed for the survey to determine the weightage factors for the model.
- Chadwick Geotechnics in providing the financial support for publishing the article.

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