TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING

Vol 56 No 2, August 2014, Pages 65–77, Paper 718

The issue of personal safety on dolomite: A probability-based evaluation with respect to transient passage in a city centre

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For the past fifty years empirical knowledge guided the development of rules regarding population density on dolomite land. The insatiable demand for land, the improvement in transportation infrastructure and the associated need for improving the functionality of towns require that these rules on the risk of personal injury and damage to assets are revisited from a more scientific perspective. Probability theory provides a basis for decision-making in this regard.

SANS 1936:2012 defines development densities for different types of land usage, including non-residential improvement, high- and low-rise buildings and single-storey dwelling houses. The paper is devoted to public safety along the roads, thoroughfares and open spaces outside buildings in a heavily populated city centre as a study in "transient density" on dolomite land. People are transported through the city in a range of vehicles. Some people walk through the city and some appear in particular locations as dispersed groups. The densities at which people appear differ during peak hours, other times of the day, and at night.

The overall probability of fatal injury is determined by the mutually dependent probabilities of sinkhole occurrence, appearance of the sinkhole in a particular location, appearance of the sinkhole at a particular time, coincidence with the vehicle, people being unaware of the sinkhole, people falling into the sinkhole, people not being protected by the vehicle and the relative number of fatal injuries

Sinkholes are invariably caused by water-bearing services that tend to leak at isolated locations, as a result of which only one sinkhole occurs at a time in a particular stretch of land. In developed land the leaky service and the sinkhole are generally repaired soon after the sinkhole has occurred, which precludes the recurrence of sinkholes in that area for a very long period of time. The probability of sinkhole occurrence can therefore be evaluated on the basis of the binomial distribution. The infiltration regime that determines the sinkhole return period for this purpose is based on the water and wastewater reticulation infrastructure, stormwater control measures, landscaping and irrigation provisions, occurrence of impermeable pavements and dewatering protocols characteristic of a business district in a city centre.

It is shown that the probability of potential fatal injury during peak time is larger than an internationally prescribed threshold value for Inherent Hazard Classes 6, 7 and 8 for minibus taxis, buses and pedestrians at road intersections for sinkholes 10–20 m in diameter. These unacceptable cases may be resolved by marginally changing the values for some of the input probabilities that may be somewhat conservative. Alternatively, the adopted threshold level for tolerable risk could be relaxed from "As Low As Reasonably Practical" to "Slight", which may more accurately represent the *fait accompli* sense of risk in the brownfields situation in Centurion City. A further way to view the unacceptable cases is that they are largely compatible with the prescribed land usages in SANS 1936:2012, in that precautionary measures corresponding to area designations D3 + FP1, D3 + DL1 or D4 are required for all but Inherent Hazard Class 1. These requirements are fully justified for Inherent Hazard Classes 6, 7 and 8, may be somewhat conservative for Inherent Hazard Classes 4 and 5, and are quite likely too conservative for Inherent Hazard Classes 2 and 3 in the open spaces in a city centre environment. A fourth way of dealing with the unacceptable cases in a greenfields situation is to implement engineering designs to pavement structures that would mitigate the hazard.

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Keywords: sinkhole, coincidence, personal safety, risk, hazard, probability, city centre, transient passage

INTRODUCTION

The hazard that sinkholes and surface subsidences pose to public safety has for the past fifty years played a fundamental role in township development on dolomite land. Empirical knowledge guided the development of rules

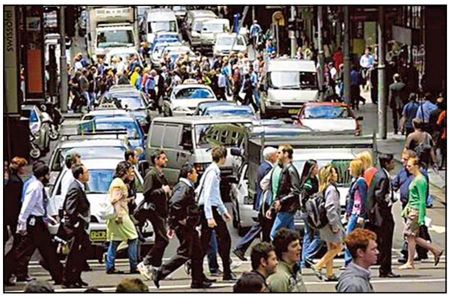

Figure 1 View of city centre during peak hour

on population and development density in different types of townships on such land. The rules were based on the observation that the likelihood that people would be affected by a sinkhole, as well as the severity of such effect, were related to the number of people who congregate in a particular area. Commercial demand for land development, the improvement in transportation infrastructure and the general need for densification to improve the functionality of towns bring people together in greater numbers and require that the empirical rules be revisited from a more scientific perspective. Probability theory informed by industry standards for sinkhole size and frequency per unit of area for different hazard classes, as propounded in SANS 1936:2012, provides the basis for such an approach.

Kirsten *et al* (2009, 2014a and 2014b) dealt with the issue of personal safety in single- and two- and three-storey residential accommodation. In the present paper the focus is on high-rise buildings commensurate with a cityscape similar to central Pretoria and Johannesburg, and with the volumes of vehicular and pedestrian traffic associated with such cities, as illustrated in the photograph in Figure 1.

In dealing with the exposure of people in residential accommodation, the likelihood of coincidence between the structure and the sinkhole is the point of departure. The likelihood of the home being occupied, structural collapse of the building, the occupants being in residence at the time and a number of occupants fatally injured, are dependent on the sinkhole occurring sufficiently close to the building to affect it. Transient density, which refers to people moving about in the open spaces between houses in cars and on foot, was not considered by Kirsten *et al* (2009, 2014a and 2014b) in dealing with single and two- and three-storey residential accommodation, because it was perceived to be low and the likelihood small that larger numbers of people would be injured out of doors in such environments. In a city centre, transient density in public spaces is very high at particular times of the day.

It is assumed in the paper that the buildings in which people are accommodated during most of the day in a city centre are safely founded and that the safety of the occupants is not compromised, even if a sinkhole were to develop directly beneath these buildings. The focus in this instance is rather on the large numbers of people who enter and exit buildings at various times of the day to occupy the roads and sidewalks and the open spaces in-between the buildings of the city in various ways and modes of transportation.

Table 1 Geological time-based assessment of sinkhole return period per 100 ha (years)

Inherent hazard class	Township	Sinkhole size (m)					
		Less than 2	2 – 5	5 – 15	15 – 25	25 – 40	Larger than 40
1	Natural	100 000	100 000	100 000	100 000	100 000	500 000
	Residential	100	100	100	4 500	27 000	135 000
	City Centre	50	50	50	2 000	12 000	60 000
2	Natural	100 000	100 000	100 000	100 000	100 000	500 000
	Residential	45	45	45	2 200	12 000	70 000
	City Centre	20	20	20	800	5 000	30 000
3	Natural	10 000	10 000	10 000	20 000	100 000	500 000
	Residential	25	25	25	800	6 000	30 000
	City Centre	10	10	10	300	2 000	12 000
4	Natural	10 000	10 000	10 000	20 000	100 000	500 000
	Residential	15	15	15	550	3 000	15 000
	City Centre	5	5	5	250	1 250	6 000
5	Natural	1 000	1 000	1 000	10 000	500 000	5 000 000
	Residential	5	5	5	150	2 500	25 000
	City Centre	1	1	2	10	100	1 000
6	Natural	1 000	1 000	1 000	10 000	200 000	1 000 000
	Residential	3	3	3	3	500	5 000
	City Centre	0.5	0.5	0.5	2	50	500
7	Natural	1 000	1 000	1 000	1 000	20 000	1 000 000
	Residential	3	3	3	3	500	5 000
	City Centre	0.5	0.5	0.5	0.5	50	500
8	Natural	800	800	800	800	10 000	100 000
	Residential	3	3	3	3	500	5 000
	City Centre	0.5	0.5	0.5	0.5	0.5	100

The purpose in the paper is to evaluate the risk of fatal injury in the various modes of transportation, and ways in which people appear in public spaces in the centre of a city on dolomite land subject to the infiltration of water peculiar to such an environment.

The infiltration regime is a fundamental determinant in the evaluation of sinkhole occurrence. Kirsten *et al* (2014a) distinguished between natural, residential and city centre infiltration regimes, as these are determined by the water-bearing services, measures to control stormwater, landscaping and irrigation provisions, occurrence of impermeable pavements and dewatering protocols characteristic to each regime.

The infiltration regimes are expressed in terms of potential sinkhole return periods for the eight Inherent Hazard Classes defined by Buttrick *et al* (2001), and the six sinkhole sizes as shown in Table 1. The two largest sinkhole sizes were added to the four sizes originally presented by Buttrick *et al* to extend their range. The research developments that preceded the definition of the return periods in Table 1 are presented by Kirsten *et al* (2009; 2014a).

Sinkhole occurrence is treated in this paper as a chance phenomenon, the qualifications of which are dealt with by Kirsten *et al* (2014a). It mainly needs to be observed that, as a result thereof that sinkholes are caused by water-bearing services that tend to leak at isolated locations, only one sinkhole occurs at any point in time in a neighbourhood, and that as a result of how the causes and the sinkhole itself are repaired, only that one sinkhole occurs at that location over a substantial period of time.

EVALUATION OF DOLOMITE RISK IN BUSINESS DISTRICTS

Before the advent of SANS 1936:2012 and SANS 10400:2012, the approach to developing on dolomite land was to strictly control residential development according to Inherent

Hazard Class 5 or better land, and to allow different categories of commercial development on Inherent Hazard Classes 6 and 7 land. The motivation for this was that more effort can go into foundation systems for commercial development, that better control can be exercised on wet services systems and that corporate ownership is more robust to losses suffered when things go wrong than what individual home ownership is capable of. Inherent Hazard Class 8 land was considered to be irreparably unsuitable for any formal development. The promulgation of SANS 1936:2012 and SANS 10400:2012 considerably clarified the matter and to some extent relaxed these restrictions in some respects.

A business district in principle comprises low-rise shops and offices, garages, parking lots and high-rise office and apartment buildings. An extract of the land usage requirements in Table 2 in SANS 1936 – 1:2012 on a business district including these improvements is given in Table 2. The land usage requirements in the standard are expressed in terms of maximum permissible population densities for four levels of precautionary measures represented by area designations D1, D2, D3 and D4 respectively, and are briefly defined as follows:

- D1 No precautionary measures considered
- D2 Precautionary measures prevent concentrated ingress of water into the ground
- D3 Additional precautionary measures to D2 requirements as provided for in the standard
- D4 Precautionary measures determined rationally and specifically for the particular site

It follows by inference that the maximum permissible population densities for land usage requirements D1, D2 and D3 by definition correspond to minimum population densities for land usage requirements D2, D3 and D4 respectively, i.e. for an area designation one level higher in each instance, hence the minimum inferred population densities denoted by superscript "1" in Table 2.

It can be seen in Table 2 that in all except Inherent Hazard Class 1, precautionary measures are corresponding to area designation D3 plus design level investigations FP1 and DL1 or area designation D4 required in business districts. It is required in SANS 1936 – 3:2012 that the land usage requirements apply to the entire site under development, including open areas outside buildings and all manner of infrastructure. The engineering design and construction of municipal township services and services in interconnected complexes, including stormwater management systems, roads, sewer mains and water supply systems, are specified in detail in SANS 1936 – 3:2012, irrespective of the Inherent Hazard Class. It

Table 2 Permissible land usages for city centre business districts

Inherent hazard class	Land usage	Storeys	Number of people/ha						
			Permissible land usage requirement						
			D1	D2	D2 + FP1	D3	D3 + FP1	D3 + DL1	D4
1	Shops and offices	≤ 3	0	0	Open	Open[1]	Open[1]	Open[1]	Open[1]
	Shops and offices	> 3	0	0	Open	Open[1]	Open[1]	Open[1]	Open[1]
	Garages	-	0	Open	Open[1]	Open[1]	Open[1]	Open[1]	Open[1]
	Parking lots	-	0	Open	Open[1]	Open[1]	Open[1]	Open[1]	Open[1]
	High-rise buildings	> 3	0	0	≤ 1 500	≤ 1 500[1]	≤1 500[1]	≤ 1 500[1]	≤ 1 500[1]
	High-rise buildings	3–10	0	0	≤ 800	≤ 800[1]	≤ 800[1]	≤ 800[1]	≤ 800[1]
	High-rise buildings	> 10	0	0	0	0	0	0	Open
2	Shops and offices	≤ 3	0	0	0	0	Open	Open[1]	Open[1]
	Shops and offices	> 3	0	0	0	0	Open	Open[1]	Open[1]
	Garages	-	0	0	0	0	Open	Open[1]	Open[1]
	Parking lots	-	0	0	0	Open	Open[1]	Open[1]	Open[1]
	High-rise buildings	> 3	0	0	0	0	0	0	≤ 1 500
	High-rise buildings	3–10	0	0	0	0	≤ 800	≤ 800[1]	≤ 800[1]
	High-rise buildings	>10	0	0	0	0	0	0	Open
3, 4, 5	Shops and offices	≤ 3	0	0	0	0	Open	Open[1]	Open[1]
	Shops and offices	> 3	0	0	0	0	0	0	Open
	Garages	-	0	0	0	0	Open	Open[1]	Open[1]
	Parking lots	-	0	0	0	Open	Open[1]	Open[1]	Open[1]
	High-rise buildings	> 3	0	0	0	0	0	0	≤ 1 500
	High-ise buildings	3–10	0	0	0	0	≤ 800	≤ 800[1]	≤ 800[1]
	High-ise buildings	> 10	0	0	0	0	0	0	Open
6	Shops and offices	≤ 3	0	0	0	0	Open	Open[1]	Open[1]
	Shops and offices	> 3	0	0	0	0	0	0	Open
	Garages	-	0	0	0	0	Open	Open[1]	Open[1]
	Parking lots	-	0	0	0	Open	Open[1]	Open[1]	Open[1]
	High-rise buildings	> 3	0	0	0	0	0	0	≤ 1 500
	High-rise buildings	3 – 10	0	0	0	0	0	≤ 800	≤ 800[1]
	High-rise buildings	> 10	0	0	0	0	0	0	Open
7,8	Shops and offices	≤ 3	0	0	0	0	0	0	Open
	Shops and offices	> 3	0	0	0	0	0	0	Open
	Garages	-	0	0	0	0	0	0	Open
	Parking lots	-	0	0	0	0	0	0	Open
	High-rise buildings	> 3	0	0	0	0	0	0	≤ 1 500
	High-rise buildings	3–10	0	0	0	0	0	0	≤ 800
	High-rise buildings	> 10	0	0	0	0	0	0	Open

Note 1: Minimum population densities inferred from SANS 1936-1:2012

is against this background that the purpose of the paper is to evaluate the risk of fatal injury in the various modes of transportation and appearance of people in the open spaces in a city centre.

DEFINITION OF MODES OF TRANSPORTATION, LOCATIONS AND TIMES OF EXPOSURE

The vehicles in a city centre, the locations at which the vehicles are used and the times at which people are exposed in the vehicles and on foot are defined as follows.

Vehicles

Sinkholes can affect people in different types of vehicles, such as cars, trucks, minibus taxis and buses, and by walking along or appearing as crowds in parking areas, sports fields and other open areas.

People on foot are assumed to be walking behind one another in single file or to appear in crowds. People in files or crowds are assumed to be equally far apart. Those in crowds are assumed to be in square formation.

There are as many of a particular type of vehicle per hectare as appear in terms of a particular traffic distribution pattern. A single file or a crowd of people encompassed by a sinkhole is also considered as a vehicle or mode of transport, since they are affected as a group by the sinkhole. There are as many files of people or crowds per hectare as encompassing sinkholes of a particular size can fit along a walkway or into an area without overlapping.

Locations of exposure

The places in which the various kinds of vehicles, including groups of people, occur are referred to as locations, and in this paper include roads, road intersections, sidewalks, parking areas, lanes, malls and open areas.

Times of exposure

The risk of sinkholes to people in the various types of vehicles and in the various locations referred to is considered separately during peak, day and night time to account for the daily variation in population density in public places.

TRAFFIC DISTRIBUTION REGIME

The objective of this paper is to determine the likelihood of sinkhole-induced fatal injury in a particular mode of transport or appearance in a city centre. The distribution of people moving through a city varies in terms of vehicle size and pedestrian dispersion. As a result, the likelihood of fatal injury varies across different locations in which different modes of transport carrying different numbers of passengers and different densities of pedestrians occur. The objective can therefore be met by determining the particular mode of transport and the time during which the probability of fatal injury is the largest. The frequencies of distribution for the modes of transport with lesser probabilities of fatal injury cannot be increased in isolation, because the frequencies of all the modes of transport are an integral part of the overall traffic distribution regime.

Table 3 Sinkhole return period per ha for city centre infiltration regime

Inherent hazard class	Sinkhole Size (m)					
	Less than 2	2 – 5	5 – 15	15 – 25	25 – 40	Larger than 40
1	5 000	5 000	5 000	5 000	5 000	5 000
2	1 000	1 000	1 000	1 000	2 000	2 000
3	1 000	1 000	1 000	1 000	2 000	2 000
4	500	500	500	500	1 000	10 000
5	100	100	200	1 000	10 000	100 000
6	50	50	50	200	5 000	50 000
7	50	50	50	50	5 000	50 000
8	50	50	50	50	50	10 000

Table 4 Probability of exceeding T-year event at least once in 70 years – p_1

Inherent hazard class	Sinkhole Size (m)					
	Less than 2	2 – 5	5 – 15	15 – 25	25 – 40	Larger than 40
1	1	1	1	1	1	1
2	7	7	7	7	3	3
3	7	7	7	7	3	3
4	13	13	13	13	7	1
5	51	51	30	7	1	0
6	76	76	76	30	1	0
7	76	76	76	76	1	0
8	76	76	76	76	76	1

DETERMINATION OF PROBABILITY OF FATAL INJURY

The probability of fatal injury in a particular vehicle and location, and at a particular time, is determined by the joint occurrence of eight dependent events as represented in the following Expression.

$$P_{location,vehicle,time} = P_1 P_{2,location} P_{3,time} P_{4,location,vehicle,time} P_{5,awareness} P_{6,vehicle} P_{7,vehicle} P_{8,vehicle} \quad (1)$$

The component probabilities may be defined as follows:

- P_1
  Probability of sinkhole occurring
- $P_{2,location}$
  Probability of sinkhole appearing at a particular location
- $P_{3,time}$
  Probability of sinkhole appearing at a particular time
- $P_{4,location,vehicle,time}$
  Probability of sinkhole coinciding with a vehicle
- $P_{5,awareness}$
  Probability of people not aware of sinkhole
- $P_{6,vehicle} = R_{sizeofvehicle} R_{pavementfails}$
  Probability of people falling into sinkhole
- $R_{sizeofvehicle}$
  Probability of sinkhole being larger than vehicle
- $R_{pavementfails}$
  Probability of supporting pavement failing structurally
- $P_{7,vehicle}$
  Probability of vehicle not providing protection to people
- $P_{8,vehicle}$
  Relative number of people sustaining fatal injury in a particular vehicle

The subscript "location" denotes the following specific locations that are separately provided for in subsequent expressions:

- "cross" roads in intersections
- "road" roads outside intersections
- "inter" walkways in intersections
- "side" sidewalks outside intersections
- "lane" lanes and malls
- "park" open parking areas
- "next" stands outside, but adjoining buildings
- "open" stands outside, but away from buildings

Figure 2 Sinkhole in natural infiltration regime (north of Carletonville, South Africa)

Figure 3 Sinkhole in residential infiltration regime (Centurion, South Africa)

- "under" under buildings

The subscript "vehicle" denotes the following specific vehicles that are separately provided for in subsequent expressions:

- "car" cars
- "truck" trucks
- "taxi" minibus taxis
- "bus" buses
- "file" group of people in single file encompassed by a sinkhole
- "crowd" group of people in square formation in crowds encompassed by a sinkhole

The subscript "time" denotes the following specific times that are separately provided for in subsequent expressions:

- "peak" peak periods during the day
- "day" daytime outside peak periods
- "night" night-time (12 out of 24 hours)

The probabilities of fatal injury per hectare at a particular time for all the vehicles of a particular type, but in different locations, should be combined as independent events as the overall probability of fatal injury $P_{vehicle,time}$ for that particular vehicle in different locations. Let "location-1", "location-2"………… "location-n" denote the number of locations, n, in which the particular type of vehicle appears at a particular time. The overall probability of fatal injury may then be expressed as follows in Expression [2] based on Expression [1]. Expression [2] applies separately for the different types of vehicles (cars, trucks, taxis, buses, pedestrians in single file and pedestrians in crowds), and for every one of the different times (peak, day and night). The locations for cars, trucks, taxis and buses include roads and road intersections. The locations for pedestrians in single file include pedestrian crossings in road intersections, sidewalks, lanes, parks and areas outside buildings. The locations for pedestrians in crowds include parks and open areas outside buildings.

Figure 4 Sinkhole in city centre infiltration regime (Guatemala City, Guatemala)

$$P_{vehicle,time} = 1 - (1 - p_{location-1,vehicle,time})(1 - p_{location-2,vehicle,time})\ldots(1 - p_{location-n,vehicle,time}) \quad (2)$$

PROBABILITY OF SINKHOLE OCCURRENCE (P_1)

An event of recurrence interval T years, i.e. a T-year event, is an event of such magnitude that the average time between events of larger magnitude is T years. This length of time is also referred to as the return period. The events considered in this paper refer to sinkholes in intervals of increasing diameter. Reference to a T-year event is therefore with regard to the occurrence of a size of sinkhole in a particular interval.

Let D denote the lifetime of a city centre development. The probability that a T-year event will be exceeded at least once in the lifetime of the development is given by Expression [3]. It is not necessary to consider the occurrence of more than one sinkhole in a business district, because of the way in which sinkholes occur and are repaired, as explained by Kirsten *et al* (2014a). A lifetime is defined as 70 years, i.e. D = 70 in Expression [3].

$$P_1 = 1 - (1 - \frac{1}{T})^D \quad (3)$$

The sinkhole return period per 100 hectares is shown in Table 1 for three comparative regimes of infiltration, namely natural, residential and city centre, as presented by Kirsten *et al* (2014a). Photographs of sinkholes in the three regimes are presented in Figures 2, 3 and 4. The infiltration regime for a city centre development represents the conditions around the buildings and in the

Figure 5 Effect of broken sewer on formation of sinkhole (Pretoria, South Africa)

public spaces in a business district. The corresponding return periods per hectare, T^3, given in Table 3 were obtained by substituting the return periods, T^1, from Table 1 in the expression $T^1=N/[(1/100)N/T^1]=100T^1$. The probabilities, $P_{1,}$ of exceeding the T-year sinkhole sizes at least once in a lifetime of 70 years are determined as shown in Table 4 from Expression [3].

FREQUENCY OF SINKHOLE APPEARING IN SPECIFIC LOCATION (P_2)

Sinkholes are subjectively assumed by engineering judgement of the performance of the wet services to appear in the various locations considered at the following frequencies:

$$P_{2,cross} \propto 25 = 16\% \quad (4)$$

$$P_{2,road} \propto 25 = 16\%$$

$$P_{2,inter} \propto 50 = 32\%$$

$$P_{2,side} \propto 25 = 16\%$$

$$P_{2,lane} \propto 5 = 3.2\%$$

$$P_{2,park} \propto 1 = 0.6\%$$

$$P_{2,next} \propto 0.1 = 0.1\%$$

$$P_{2,open} \propto 0.1 = 0.1\%$$

$$P_{2,under} \propto 25 = 16\%$$

The effect of leaking services is illustrated in the photograph in Figure 5 in which a broken sewer gave rise to a 5 m sinkhole.

FREQUENCY OF SINKHOLE APPEARING AT PARTICULAR TIME (P_3)

Two four-hour peak periods are assumed to occur at the start and end of the day, leaving daytime and night-time periods of four and twelve hours respectively. The frequencies of a sinkhole appearing during the three periods are therefore as follows:

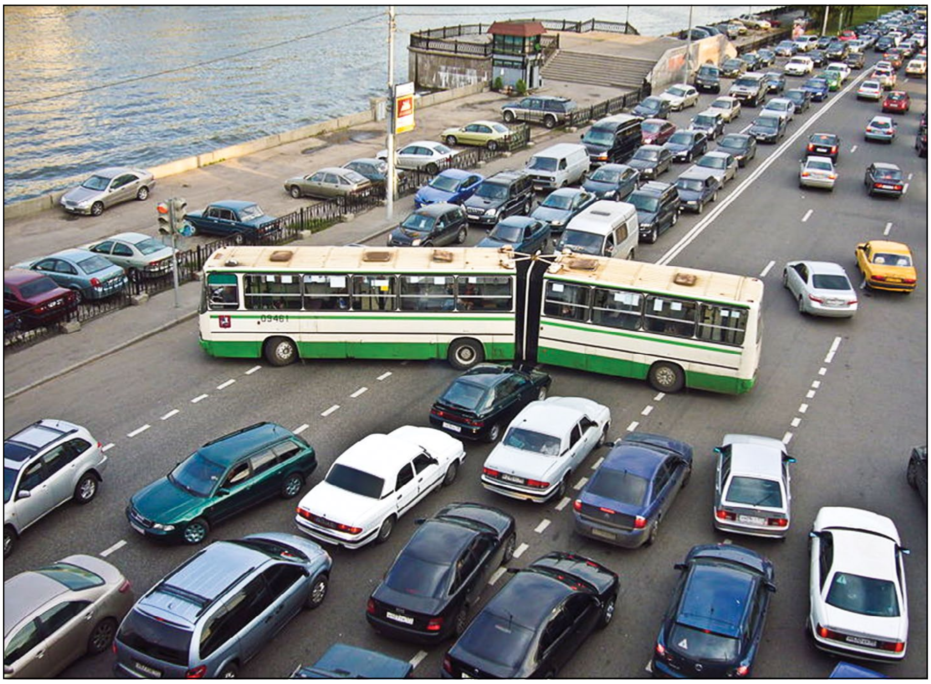

Figure 6 Aerial view of typical traffic congestion at peak time in a city centre

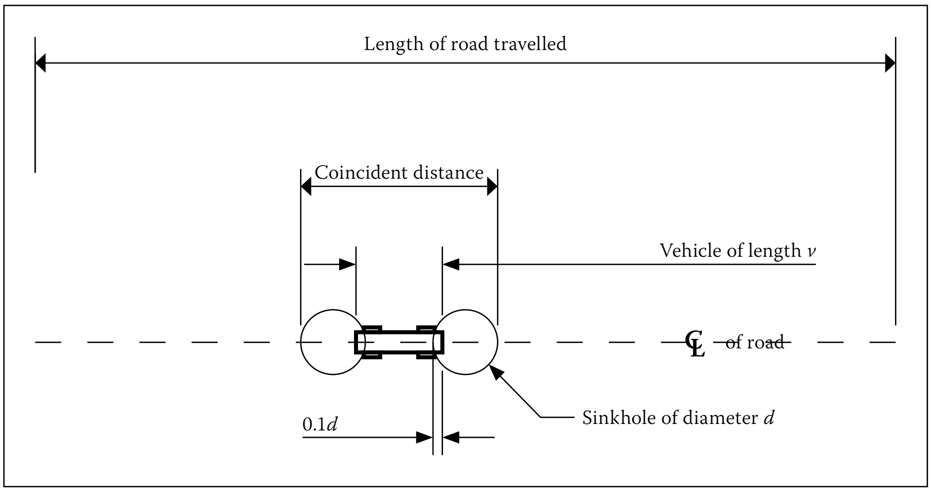

Figure 7 Coincidence of sinkhole with vehicle

$$P_{3,peak} = 8 \div 24 = 0.33 \quad (5)$$

$$P_{3,day} = 4 \div 24 = 0.17$$

$$P_{3,night} = 12 \div 24 = 0.50$$

PROBABILITY OF SINKHOLE COINCIDING WITH VEHICLE (P_4)

An aerial view of traffic congestion at peak time in a city centre is shown in the photograph in Figure 6. A sinkhole is defined to coincide with a vehicle if it overlaps by 10% of its diameter in front and behind the vehicle, as shown in Figure 7. The overall distance ($v+1.8d$) may be referred to as the coincident distance. The diameter of the sinkhole is denoted by d and v is the length of the vehicle. The probability of a sinkhole coinciding with a particular kind of vehicle is defined as the proportion of the coincident distance to the length of road along which the vehicle is travelling, but which is not occupied by vehicles of another kind, multiplied by the likelihood of the sinkhole occurring in the stretch of road occupied by vehicles of the same kind. Different lanes in the same or opposite direction are taken as separate lengths of road along which the vehicle can travel. The probabilities of a sinkhole coinciding with other similar vehicles along the same length of road are taken as independent events and are accordingly added. Therefore, for any one kind of vehicle of which there are n along the length of road considered:

$$P_4 = 1 - [1 - \frac{(v + 1.8d)}{(L - L_{other})}(1 - \frac{L_{other}}{L})]^n$$

$$= \{1 - [1 - \frac{(v + 1.8d)}{L}]^n\} \quad (6)$$

The probability of a sinkhole coinciding with a particular kind of vehicle in various locations at a particular time of day may therefore be expressed as follows:

Figure 8 View of typical pedestrian density during peak hour in a city centre

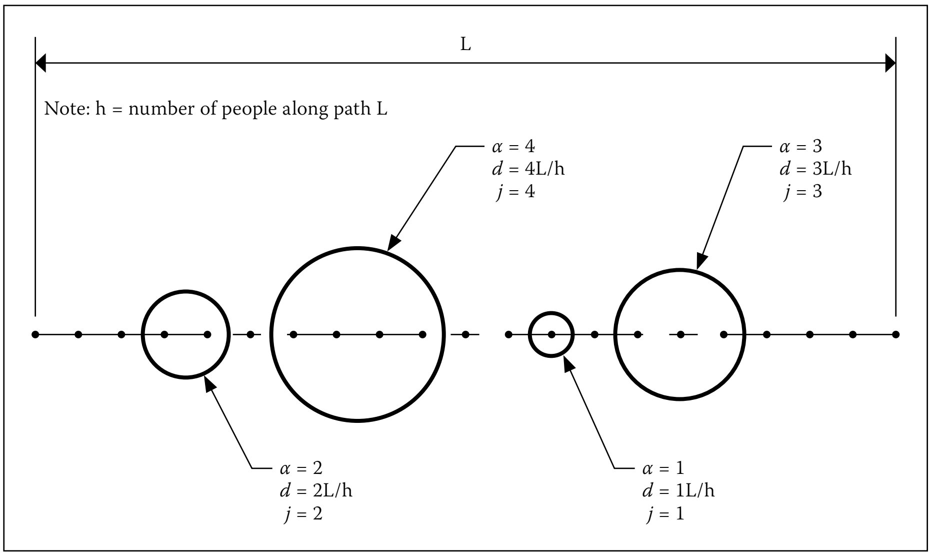

Figure 9 Coincidence of various sizes of sinkhole with people walking in single file

$$P_{4,location,vehicle,time} = \{1 - [1 - \frac{(v_{vehicle} + 1.8d)}{L_{location}}]^{n_{location,vehicle,time}}\} \quad (7)$$

PROBABILITY OF SINKHOLE COINCIDING WITH FILES OF PEOPLE (P_4)

A view of pedestrian density during peak hour in a city centre is shown in the photograph in Figure 8. The probability of a sinkhole coinciding with a group of people walking in single file along a path as shown in Figure 9 is defined as the proportion of the diameter of the sinkhole to the length of the path. The number of persons within the diameter of the sinkhole defines the size of the group, *j*. The diameter of the sinkhole, *d*, is a multiple α of the spacing between people, $L \div h$, where L denotes the length of the path and h the number of people along the path. Thus:

$$d = \alpha \frac{L}{h} \qquad d < L \qquad (8)$$

The number of people equally far apart within length *d* is by definition given by,

$$j = \alpha = \frac{hd}{L} \qquad (9)$$

The number of groups of people, g, of size *j* along the path is given by:

$$g = h - \alpha + 1 = \frac{hd}{L} + 1 \qquad d < L \qquad (10)$$

The probability that a sinkhole of diameter *d* coincides with any one of *g* number groups of people of size *j* along a path of length *L* along which *h* number people are present at equal distances from one another is therefore given by:

$$P_4 = 1 - (1 - \frac{d}{L})^g \qquad d < L \qquad (11)$$

The probability of a sinkhole coinciding with groups of people along a particular walkway in various locations at a particular time of day may therefore be expressed as follows:

$$P_{4,location,time} = [1 - (1 - \frac{d}{L_{location}})^{g_{location,time}}] \quad (12)$$

PROBABILITY OF SINKHOLE COINCIDING WITH CROWDS (P_4)

The probability of a sinkhole coinciding with a group of people in a park in square formation, as shown in Figure 10, is defined as the proportion of the area of the sinkhole to that of the park. The number of persons within the diameter of the sinkhole defines the size of the group, *j*. The diameter of the sinkhole, *d*, is a multiple β of the grid spacing $(A \div h)^{0.5}$, where A denotes the area of the park and h the number of people in the park in square formation. Thus,

$$d = \beta \sqrt{\frac{A}{h}} \qquad d < \sqrt{A} \qquad (13)$$

The number of people in square formation within an area d^2 is by definition given by:

$$j = \beta^2 = \frac{hd^2}{A} \qquad d < \sqrt{A} \qquad (14)$$

Approximating the area of a sinkhole of diameter d by d^2 does not give rise to a significant error in the context of the problem, since the number of people circumscribed by a sinkhole does not vary for variations of the diameter of the sinkhole within grid intervals. Adding the corners of an area d^2 is no worse than not accounting for a change in the number of people circumscribed for variations of the diameter of a sinkhole between grid intervals.

The number of groups of people, *g*, of size *j* in the park is given by:

$$g = (\sqrt{h} - \beta + 1)^2 = (\sqrt{h} - d\sqrt{\frac{A}{h}} + 1)^2 \qquad d < \sqrt{A} \qquad (15)$$

The probability that a sinkhole of diameter *d* coincides with any one of *g* number of groups of people of size *j* in a park of area *A* in which *h* number of people are present in square formation is therefore given by:

$$P_4 = 1 - (1 - \frac{d^2}{A})^g \qquad (16)$$

The probability of a sinkhole coinciding with crowds of people in square formation in open

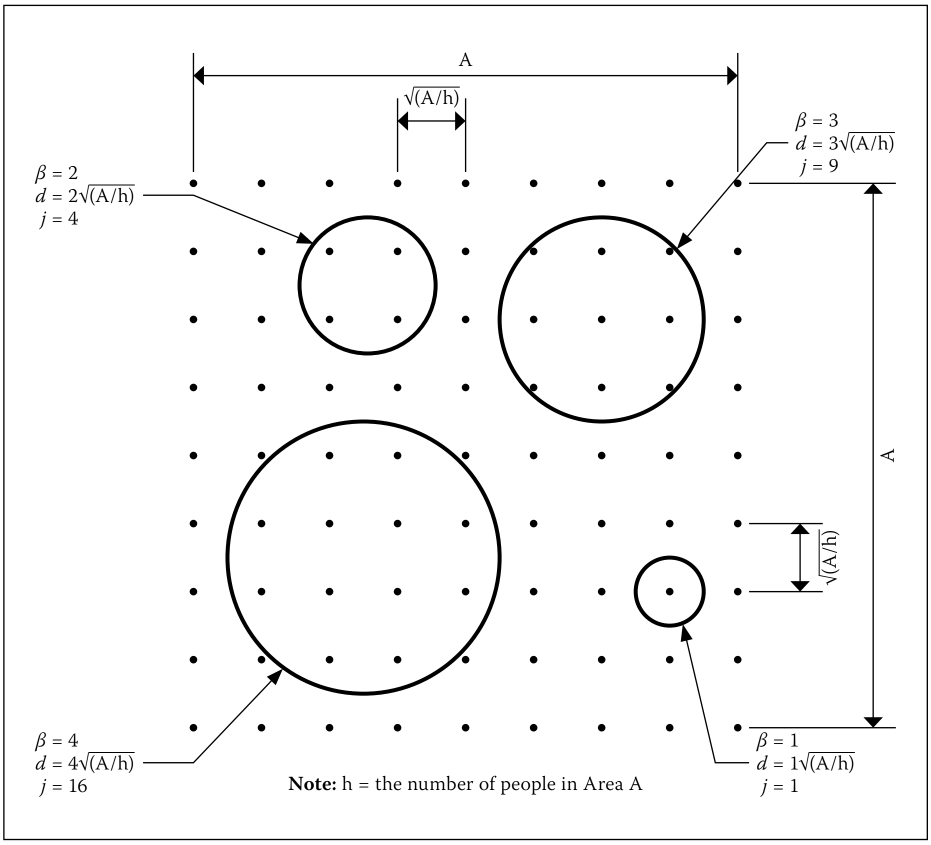

Figure 10 Coincidence of various sizes of sinkhole with crowds of people in square formation

Table 5 Probability of sinkhole larger than vehicle ($p_{vehiclesize}$)

Place	Sinkhole size (m)					
D	1	3	10	20	32.5	50
Car	1.0e–06	⅓	1.0	1.0	1.0	1.0
Truck	1.0e–06	1.0e–06	1.0	1.0	1.0	1.0
Minibus taxi	1.0e–06	⅓	1.0	1.0	1.0	1.0
Bus	1.0e–06	1.0e–06	1.0	1.0	1.0	1.0
Pedestrian	1.0	1.0	1.0	1.0	1.0	1.0

Table 6 Probability of pavement failing ($p_{pavementfails}$)

Place	Sinkhole size (m)					
D	1	3	10	20	32.5	50
Car	0.01	0.1	1.0	1.0	1.0	1.0
Truck	0.01	0.1	1.0	1.0	1.0	1.0
Minibus taxi	0.01	0.1	1.0	1.0	1.0	1.0
Bus	0.01	0.1	1.0	1.0	1.0	1.0
Pedestrian	0.01	0.1	1.0	1.0	1.0	1.0

Table 7 Probability of people falling into sinkhole (p_6)

Place	Sinkhole size (m)					
D	1	3	10	20	32.5	50
Car	1.0e–08	0.033333	1.0	1.0	1.0	1.0
Truck	1.0e–08	1.0e–07	1.0	1.0	1.0	1.0
Minibus taxi	1.0e–08	0.033333	1.0	1.0	1.0	1.0
Bus	1.0e–08	1.0e–07	1.0	1.0	1.0	1.0
Pedestrian	0.01	0.1	1.0	1.0	1.0	1.0

Figure 11 Size of typical passenger vehicle relative to 10 m sinkhole (Lisbon, Portugal)

Figure 12 Typical capping of road pavement over sinkhole (Centurion, South Africa)

areas in various locations at a particular time of day may therefore be expressed as follows:

$$P_{4,location,time} = [1 - (1 - \frac{d}{A_{location}})^{g_{location,time}}] \quad (17)$$

PROBABILITY OF PEOPLE UNAWARE OF SINKHOLE (P_5)

It is assumed that people are 100% unaware of sinkholes that occur in any location and at any time. Thus, $P_5 = 1.0$.

PROBABILITY OF PEOPLE FALLING INTO SINKHOLE (P_6)

The probability that people fall into a sinkhole presupposes that the sinkhole is larger than the vehicle, and that the pavement fails as mutually dependent events in terms of the following expression:

$$P_{6,vehicle} = P_{vehiclesize} P_{pavementfails} \quad (18)$$

The component probabilities in this expression are subjectively assumed by engineering judgement to have the values given in Tables 5 and 6, and the resulting probabilities of people falling into a sinkhole in Table 7 ("pedestrian" refers to both files and crowds of people).

The size of a vehicle relative to a sinkhole is illustrated in the photograph in Figure 11 in which a large passenger vehicle has fallen some distance into a 10 m sinkhole. The capping that a road pavement typically provides over a sinkhole is illustrated in the

Table 8 Probability of injury sustained by people (p_8)

Place	Sinkhole size (m)					
D	1	3	10	20	32.5	50
Car	0.001	0.1	0.3	0.3	0.5	0.5
Truck	0.0001	0.01	0.1	0.2	0.3	0.3
Minibus taxi	0.001	0.1	0.3	0.3	0.5	0.5
Bus	0.0001	0.01	0.1	0.2	0.3	0.3
Pedestrian	0.5	0.5	0.5	0.5	0.5	0.5

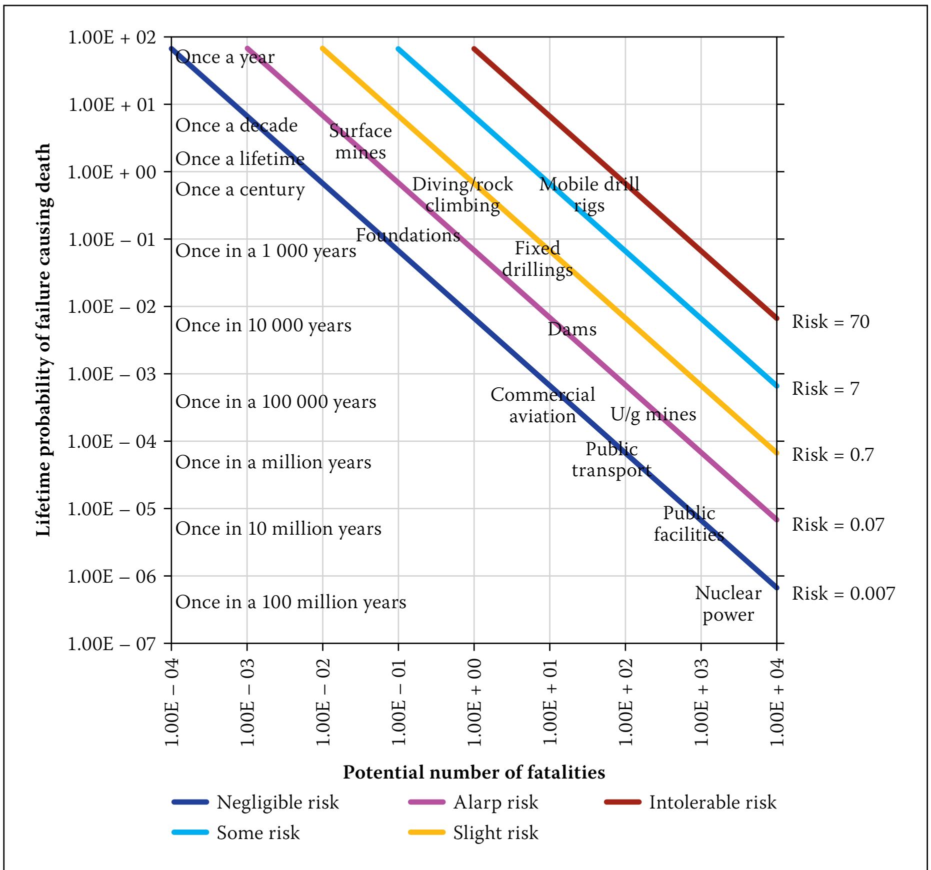

Figure 13 Risk criteria for fatal injury (after Whitman 1984)

photograph in Figure 12, taken on the old Pretoria to Johannesburg road.

PROBABILITY OF VEHICLE NOT PROVIDING PROTECTION (P_7)

It is presumably 100% certain that none of the vehicles provide any protection against fatal injury, i.e. $P_7 = 1.0$. Even if the vehicle is not buried or badly deformed, the passengers would still be severely knocked around when a vehicle travelling at speed lands in a sinkhole.

PROBABILITY OF FATAL INJURY (P_8)

Values for the probabilities of fatal injury, $P_{8,vehicle}$, are subjectively assumed by engineering judgement to be as given in Table 8 for various vehicles and sinkhole sizes. It is moot whether the values are not somewhat conservative, especially for the mid-range sinkhole sizes.

EVALUATION OF POPULATION DENSITY

Let $s_{vehicle}$ denote the number of people in a particular vehicle, and $M_{vehicle}$ the potential number of lives lost in the vehicle due to a sinkhole. It follows by definition that $M_{vehicle}$ may be expressed as follows in terms of $s_{vehicle}$ and the probability of fatal injury, $P_{8,vehicle}$.

$$M_{vehicle} = s_{vehicle} P_{8,vehicle} \quad (19)$$

Let R denote the level of risk considered in terms of Figure 13, and $P_{vehicle}$ the threshold lifetime probability of fatal injury per hectare for a potential number of lives lost per hectare of $M_{vehicle}$. Then in terms of Figure 13:

$$P_{vehicle} = \frac{R}{M_{vehicle}} \quad (20)$$

It follows from Expression [19] that:

$$P_{vehicle} = \frac{R}{s_{vehicle} P_{8,vehicle}} \quad (21)$$

It should be observed that,

$$P_{file} = \frac{R}{s_{file} P_{8,file}}, \text{ where} \quad (22)$$

$$S_{file} = \frac{s_{inter}^2 + s_{side}^2 + s_{lane}^2}{s_{int\,er} + s_{side} + s_{lane}}, \text{ and} \quad (23)$$

$$P_{8,file} = P_{8,inter} = P_{8,side} = P_{8,lane} \quad (24)$$

Similar relationships apply to crowds.

The probability of fatal injury per hectare for a particular vehicle and time, $P_{vehicle,time}$, should be $\leq P_{vehicle}$, the threshold probability of fatal injury per hectare for the particular risk level considered, R. The number of people per hectare for whom this condition is satisfied are given from Expression [2] by:

$$F = \frac{R}{\begin{array}{c} s_{vehicle} P_{8,\mathrm{vehicle}} \\ [1 - (1 - p_{location-1,vehicle,time}) \\ (1 - p_{location-2,vehicle,time}) .... \\ (1 - p_{location-\mathrm{n},vehicle,time})] \end{array}} \geq 1.0 \quad (25)$$

The number of people in each vehicle and time slot may be varied until this condition is satisfied. The vehicle and time slot at which the potential number of lives lost is the least at $F = 1.0$, is the determining criterion. As an alternative approach, the likelihood of a sinkhole occurring can be reduced by mitigating the infiltration of water, propounded in SANS 1936:2012, or by upgrading the pavement to competently bridge over sinkholes of a pre-determined size.

DISTRIBUTION OF VEHICULAR AND PEDESTRIAN TRAFFIC IN A CITY CENTRE

Typical values for the parameters for the daily distribution of vehicular and pedestrian traffic in a city centre are given in Table 9, for typical layouts for the following four types of development, namely, single-storey dwelling houses, two- and four-storey dwelling units, city centre residential accommodation and city centre office accommodation. The symbols for the input parameters are given in the second column in Table 9. The typical layouts are shown in Figures 14 through 17. The values for the parameters in Table 9 are based on the assumption that the land is fully developed and all buildings are constructed complete as laid out. The figures are not adjusted downward for parking, because it is relatively minor.

The traffic distribution models in Table 9 are given to illustrate the different

Table 9 Distribution of vehicular and pedestrian traffic in a city centre

Item	Description	Symbol/dimension	Single-storey dwelling houses	Two/four-storey dwelling units	City centre office	City centre residential
1	Diameter of sinkhole	d (m)	Range	Range	Range	Range
2	No of people/ha accommodated		125	150	3 000	1 500
3	Duration of entry/departure	(min)	10	10	90	60
4	Entry/departure cycle time	(min)	10	10	10	10
5	Length of peak	(h)	2	2	8	4
6	Length of day	(h)	9	10	4	10
7	Length of night	(h)	13	12	12	10
8	No of road lanes available		2	2	2	2
9	No of road lanes frozen during entry/departure		0	0	1	1
10	Length of car	**v** (car) (m)	5	5	5	5
11	Length of truck	**v** (truck) (m)	10	10	10	10
12	Length of minibus taxi	**v** (taxi) (m)	8	8	8	8
13	Length of bus	**v** (bus) (m)	16	16	16	16
14	Average number of people per car	**s** (car)	2	2	2	2
15	Average number of people per truck	**s** (truck)	4	4	4	4
16	Average number of people per minibus taxi	**s** (taxi)	20	20	20	20
17	Average number of people per bus	**s** (bus)	60	60	60	60
18	Length of road inside intersection/ha	**L** (cross) (m)	50	50	200	200
19	Length of road outside intersection/ha	**L** (road) (m)	400	400	600	600
20	Length of path inside intersection/ha	**L** (inter) (m)	50	50	200	200
21	Length of path along sidewalk/ha	**L** (side) (m)	400	400	600	600
22	Length of lanes and malls/ha	**L** (lane) (m)	0	0	75	75
23	Area of parking lots/ha	**A** (park) (m^2)	0	0	300	300
24	Area on stands next to buildings/ha	**A** (next) (m^2)	1 625	1 440	0.01	0.01
25	Area on stands away from buildings/ha	**A** (open) (m^2)	4 150	5 680	0.01	0.01
26	No of cars/ha in intersection during peak	**n** (cross,car,peak)	0	2	0	2
27	No of cars/ha in intersection during day	**n** (cross,car,day)	0	0	2	1
28	No of cars/ha in intersection during night	**n** (cross,car,night)	0	0	2	1
29	No of trucks/ha in intersection during peak	**n** (cross,truck,peak)	0	0	0	1
30	No of trucks/ha in intersection during day	**n** (cross,truck,day)	0	0	1	1
31	No of trucks/ha in intersection during night	**n** (cross,truck,night)	0	0	0	0
32	No of minibus taxis/ha in intersection during peak	**n** (cross,taxi,peak)	1	1	7	6
33	No of minibus taxis/ha in intersection during day	**n** (cross,taxi,day)	0	0	3	3
34	No of minibus taxis/ha in intersection during night	**n** (cross,taxi,night)	0	0	0	0
35	No of buses/ha in intersection during peak	**n** (cross,bus,peak)	0	0	3	2
36	No of buses/ha in intersection during day	**n** (cross,bus,day)	0	0	3	2
37	No of buses/ha in intersection during night	**n** (cross,bus,night)	0	0	0	0
38	No of cars/ha in road during peak	**n** (road,car,peak)	25	13	0	6
39	No of cars/ha in road during day	**n** (road,car,day)	8	4	3	3
40	No of cars/ha in road during night	**n** (road,car,night)	2	2	3	3
41	No of trucks/ha in road during peak	**n** (road,truck,peak)	0	0	0	3
42	No of trucks/ha in road during day	**n** (road,truck,day)	0	0	3	3
43	No of trucks/ha in road during night	**n** (road,truck,night)	0	0	0	0
44	No of minibus taxis/ha in road during peak	**n** (road,taxi,peak)	2	2	17	18
45	No of minibus taxis/ha in road during day	**n** (road,taxi,day)	1	1	9	9
46	No of minibus taxis/ha in road during night	**n** (road,taxi,night)	0	0	3	3
47	No of buses/ha in road during peak	**n** (road,bus,peak)	0	1	11	6
48	No of buses/ha in road during day	**n** (road,bus,day)	0	0.5	3	3
49	No of buses/ha in road during night	**n** (road,bus,night)	0	0	0	0
50	No of people/ha in intersection during peak	**h** (inter,peak)	5	5	80	80
51	No of people/ha in intersection during day	**h** (inter,day)	5	5	40	20
52	No of people/ha in intersection during night	**h** (inter,night)	0	0	4	4
53	No of people/ha on sidewalks during peak	**h** (side,peak)	10	10	80	80
54	No of people/ha on sidewalks during day	**h** (side,day)	10	10	48	16
55	No of people/ha on sidewalks during night	**h** (side,night)	2	2	2	2
56	No of people/ha in lanes and malls during peak	**h** (lane,peak)	0	0	10	10
57	No of people/ha in lanes and malls during day	**h** (lane,day)	0	0	2	2
58	No of people/ha in lanes and malls during night	**h** (lane,night)	0	0	0	0
59	No of people/ha in parking areas during peak	**h** (park,peak)	0	0	20	20
60	No of people/ha in parking areas during day	**h** (park,day)	0	0	5	5
61	No of people/ha in parking areas during night	**h** (park,night)	0	0	1	1
62	No of people/ha next to buildings during peak	**h** (next,peak)	10	10	0	0
63	No of people/ha next to buildings during day	**h** (next,day)	0	0	0	0
64	No of people/ha next to buildings during night	**h** (next,night)	0	0	0	0
65	No of people/ha on stands in open areas during peak	**h** (open,peak)	2	2	0	0
66	No of people/ha on stands in open areas during day	**h** (open,day)	10	10	0	0
67	No of people/ha on stands in open areas during night	**h** (open,night)	0	0	0	0
68	Length of road/ha in crossings occupied during peak	(m)	8	18	104	100
69	Length of road/ha in crossings occupied during day	(m)	0	0	92	71
70	Length of road/ha in crossings occupied during night	(m)	0	0	10	5
71	Length of road/ha ex crossings occupied during peak	(m)	141	97	312	300
72	Length of road/ha ex crossings occupied during day	(m)	48	36	165	165
73	Length of road/ha ex crossing occupied during night	(m)	10	10	39	39
74	No of people/ha conveyed during peak		110	150	11 880	5 952
75	No of people/ha conveyed during day		36	58	1 252	1 128
76	No of people/ha conveyed during night		4	4	140	136
77	No of permanent occupants/ha during peak		110	150	11 880	5 952
78	No of incoming visitors/ha during peak		0	0	0	0
79	No of permanent occupants per dwelling/cluster/building		4.4	25	2 970	1 488

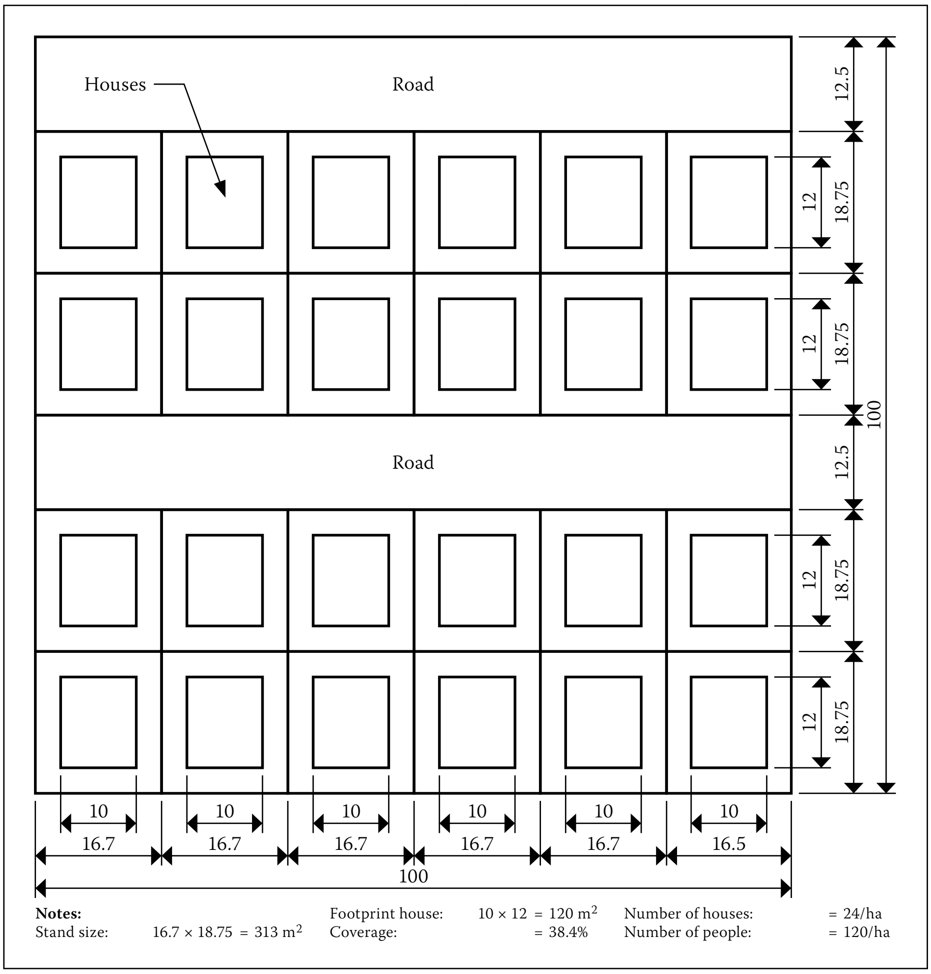

Figure 14 Typical layout of single-storey residential houses

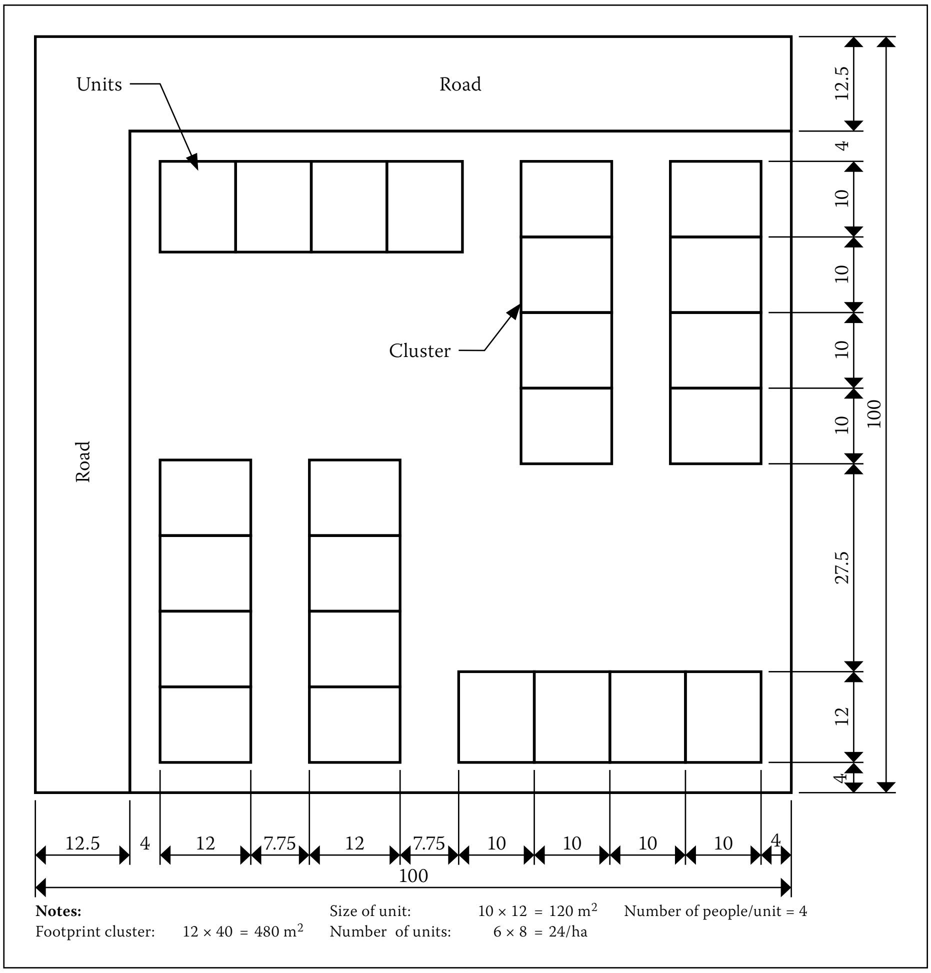

Figure 15 Typical layout of two- and three-storey residential units

population densities in the various township types and to enable the theory presented in this paper to be illustrated in principle. The traffic distribution models need to be verified in terms of real-life situations. The findings on one of these models, presented further on, should not be considered as definitive of the conditions and situation in any city centre located on dolomite.

The transportation of people to/from city centre accommodation during peak time is based only on half of the length of roads and road intersections to allow for loading and off-loading of passengers, and for continuous movement of traffic. In all other instances the full lengths of roads and road intersections are taken to be available for the transportation of people. The overall lengths of trains or vehicles in single file are greatest during peak time and are equal to the total lengths of the intersections and the roads. Cycle times are also only considered to apply to the transportation of people to/from city centre accommodation during peak time. Otherwise they do not apply.

All the people are assumed to be vacated by way of vehicles and on foot in an hour from high-rise residential buildings and in an hour and a half from high-rise office buildings in cycle times of 10 minutes. The total number of people in the various kinds of vehicles in intersections and on roads is therefore equal to the total number of occupants in the buildings. The people shown in Table 9 in intersections, on sidewalks, in lanes and malls, in parking areas, outside buildings and on stands in open areas represent the influx into the city centre area in addition to the permanent occupants in buildings.

EVALUATION OF PROBABILITY OF INJURY IN A CITY CENTRE

Based on the input values in Table 9 for a city centre office development, the values for parameter *F* in Expression [26] for the various places, times of day and sinkhole sizes are respectively given in Tables 10, 11 and 12 for Inherent Hazard Classes 6, 7 and 8 for a risk factor R = 0.07, corresponding to a level of risk "As Low As Reasonably Practical". This enables the particular vehicles and time slots for which F < 1.0 to be readily identified as highlighted in blue.

The findings may be summarised as follows:

Parameter F is a minimum turning point phenomenon, as expected for all instances considered. The minimum turning point for parameter F corresponds generally to a sinkhole diameter of 10–20 m.

Unacceptable cases occur only for minibus taxis, buses and files of people, which

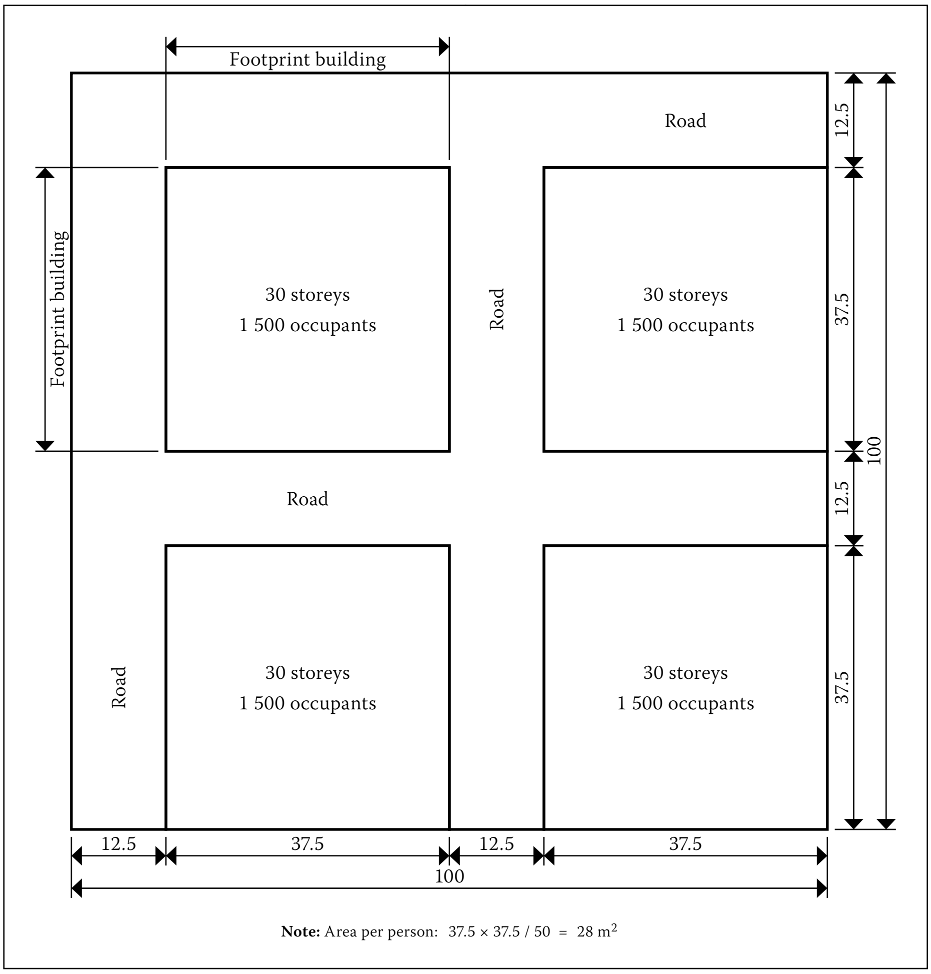

Figure 16 Typical layout of multi-storey residential buildings in a city centre

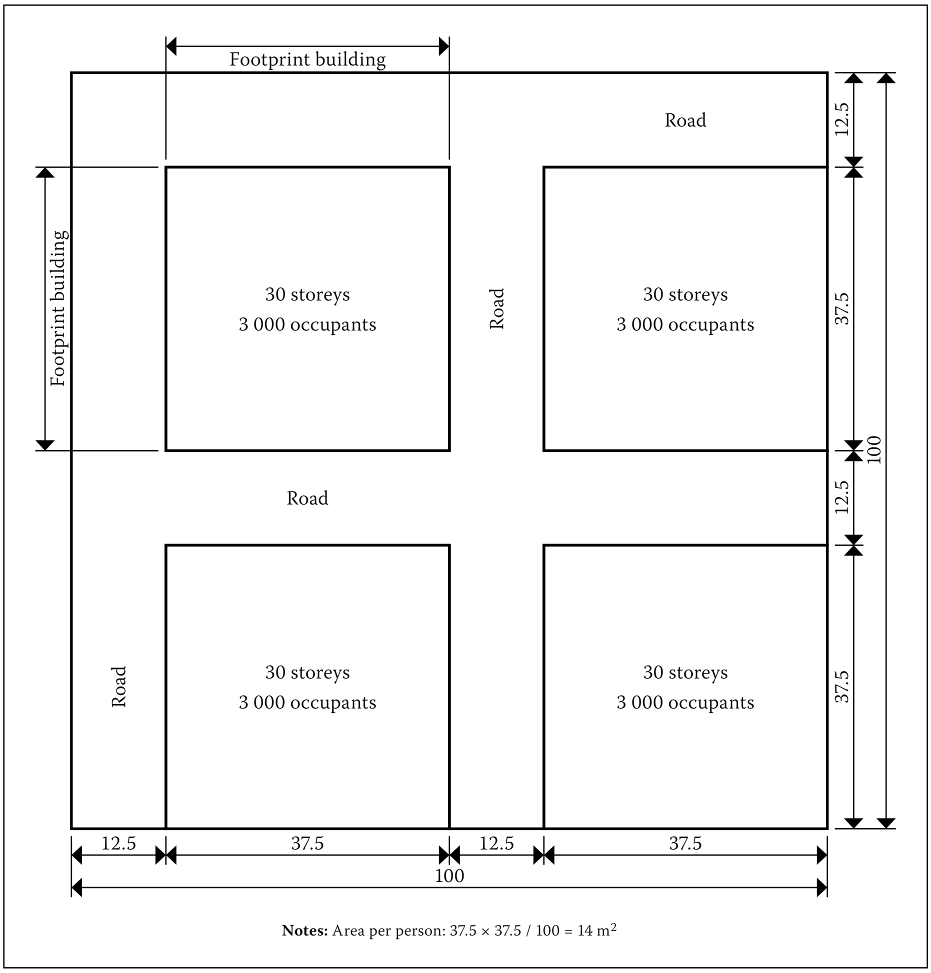

Figure 17 Typical layout of multi-storey office buildings in a city centre

can be shown to relate largely to pedestrians at intersections.

The number of unacceptable cases increases with Inherent Hazard Class.

Although not shown, it can be confirmed that no unacceptable cases occur for the development considered (high-rise offices) for Inherent Hazard Classes 1 through 5. One minimally ($F > 0.9$) and two moderately ($0.7 \leq F \leq 0.9$) unacceptable cases occur for Inherent Hazard Class 6 as evident from Table 10. Two moderately ($0.7 \leq F \leq 0.9$), two considerably ($0.5 \leq F \leq 0.7$) and one highly ($0.3 \leq F \leq 0.5$) unacceptable case/s occur for Inherent Hazard Class 7 as shown in Table 11. One minimally ($F > 0.9$), three moderately ($0.7 \leq F \leq 0.9$), four considerably ($0.5 \leq F \leq 0.7$), one highly ($0.3 \leq F \leq 0.5$) and three totally ($F < 0.3$) unacceptable cases occur for Inherent Hazard Class 8 as evident from Table 12. The ranges given above for factor F are chosen in terms of subjective engineering judgement.

The unacceptable cases referred to above may be dealt with in a number of ways. The values adopted for probabilities, P_5, people not being aware of sinkholes, P_6, people falling into sinkholes, P_7, conveyance not offering any protection, and possibly P_8, people fatally injured, may in the first instance be considered to be conservative, especially for sinkholes larger than 10 m in diameter. Since marginal changes in these values will resolve the observed unacceptable cases, it should be carefully considered whether such changes could be convincingly motivated.

It should in the second instance be observed that the unacceptable cases are a result of the level of risk, "As Low As Reasonably Practical", adopted, for which $R = 0.07$, and that the unacceptable cases would be resolved if a "Slight" level of risk for which $R = 0.7$ from Figure 13 is instead adopted. It may be that the general perception of the risk of fatal injury in the open spaces in Centurion City as a brownfields situation corresponds more accurately as *fait accompli* to "Slight" or even "Some" risk than "As Low As Reasonably Practical". The level of risk considered does not mean that fatal injuries will unavoidably occur in proportion thereto.

A third way of viewing the unacceptable cases is that they are by and large compatible with the land usage requirements for business districts as summarised in Table 2, in which precautionary measures corresponding to area designations D3 + FP1, D3 + DL1 and D4 are required for all except Inherent Hazard Class 1 in a business district. This requirement echoes the unacceptable risks of fatal injury in Inherent Hazard Classes 6, 7 and 8; may be somewhat conservative in respect of Inherent Hazard Classes 4 and 5;

Table 10 Factor F for city centre business district – inherent hazard Class 6

Inherent hazard class	Sinkhole diameter	Time slot	Vehicles				Pedestrians	
			Car	Truck	Taxi	Bus	File	Crowd
6	1	Peak	v large	v large	v large	v large	2 890	v large
		Day	v large	v large	v large	v large	19 793	v large
		Night	v large	v large	v large	v large	v large	v large
6	3	Peak	v large	v large	370	v large	44	5 904
		Day	34 125	v large	1 399	v large	261	v large
		Night	11 375	v large	2 646	v large	5 509	v large
6	10	Peak	v large	v large	0.84	3.21	0.84	27
		Day	59	317	2.88	9.82	3.86	265
		Night	20	v large	5.16	v large	54	619
6	20	Peak	v large	v large	1.59	1.51	0.98	17
		Day	88	125	4.83	4.44	4.04	132
		Night	29	v large	8.04	v large	39	221
6	32.5	Peak	v large	v large	10	11	12	135
		Day	461	810	28	32	49	1 076
		Night	154	v large	42	v large	359	1 794
6	50	Peak	v large	v large	97	98	80	563
		Day	3 325	5 655	225	260	310	4 502
		Night	1 108	v large	302	v large	1 790	7 503

Table 11 Factor F for city centre business district – inherent hazard Class 7

Inherent hazard class	Sinkhole diameter	Time slot	Vehicles				Pedestrians	
			Car	Truck	Taxi	Bus	File	Crowd
7	1	Peak	v large	v large	v large	v large	2 890	v large
		Day	v large	v large	v large	v large	19 793	v large
		Night	v large	v large	v large	v large	v large	v large
7	3	Peak	v large	v large	370	v large	44	5904
		Day	34 125	v large	1 399	v large	261	v large
		Night	11 375	v large	2 646	v large	5 509	v large
7	10	Peak	v large	v large	0.84	3.21	0.84	27
		Day	59	317	2.88	9.82	3.86	265
		Night	20	v large	5.16	v large	54	619
7	20	Peak	v large	v large	0.62	0.59	0.39	6
		Day	34	49	1.89	1.74	1.59	52
		Night	12	v large	3.14	v large	15	86
7	32.5	Peak	v large	v large	10	11	12	135
		Day	461	810	28	32	49	1 076
		Night	154	v large	42	v large	359	1 794
7	50	Peak	v large	v large	97	98	80	563
		Day	3 325	5 655	225	260	310	4 502
		Night	1 108	v large	302	v large	1 790	7 503

Table 12 Factor F for city centre business district – inherent hazard Class 8

Inherent hazard class	Sinkhole diameter	Time slot	Vehicles				Pedestrians	
			Car	Truck	Taxi	Bus	File	Crowd
8	1	Peak	v large	v large	v large	v large	2 890	v large
		Day	v large	v large	v large	v large	19 793	v large
		Night	v large	v large	v large	v large	v large	v large
8	3	Peak	v large	v large	370	v large	44	5 904
		Day	34 125	v large	1 399	v large	261	v large
		Night	11 375	v large	2 646	v large	5 509	v large
8	10	Peak	v large	v large	0.84	3.21	0.84	27
		Day	59	317	2.88	9.82	3.86	265
		Night	20	v large	5.16	v large	54	619
8	20	Peak	v large	v large	0.62	0.59	0.39	6.47
		Day	34	49	1.89	1.74	1.59	52
		Night	12	v large	3.14	v large	15	86
8	32.5	Peak	v large	v large	0.19	0.21	0.23	2.47
		Day	8.48	14.89	0.51	0.59	0.91	20
		Night	2.84	v large	0.78	v large	6.62	33
8	50	Peak	v large	v large	19	20	16	113
		Day	667	1 134	45	52	62	903
		Night	222	v large	61	v large	359	1 505

and is quite likely too conservative in respect of fatal injury in Inherent Hazard Classes 2 and 3 in the open spaces in a city centre environment.

A fourth way of dealing with the unacceptable cases in a greenfields situation is to implement engineering designs to pavement structures that would mitigate the hazard.

CONCLUSION

The objective of this paper is to present a methodology in terms of which the various factors that determine the risk of fatal injury in the open spaces in a city centre, due to a sinkhole, can be rigorously accounted for, based on probability theory and in terms of which it can in principle be shown how mathematical modelling can be applied to address some of the issues on personal safety that are involved. The values for the underlying parameters are estimates based on subjective engineering judgement and can be adjusted considerably. However, the overall result of the proposed methodology based on the parameter values considered is in principle compatible with long-standing observation by the authors.

ACKNOWLEDGEMENTS

The support of the Council for Geoscience to undertake the work described in this paper is gratefully acknowledged. The contribution that Dr Kleywegt made to the development of the geological time-based sinkhole return periods is in particular sincerely appreciated.

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