

Proposed method for dolomite land hazard and risk assessment in South Africa

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This paper presents a Proposed Method for Dolomite Land Hazard and Risk Assessment for characterising the potential stability of dolomite land, which is based on the Method of Scenario Supposition proposed by Buttrick and Van Schalkwyk (1995). The Proposed Method considers risk as well as hazard and reviews the classification of sites in terms of Dolomitic Area Designations as defined in the National Home Builders Registration Council's Home Building Manual (NHBRC 1999). The Proposed Method requires the evaluation of site geological conditions, provides a deductive framework within which professional judgement must be exercised, and offers a tool for the quantification and management of development risk. The provisions of the Housing Consumer Protection Measures Act (Act 95 of 1998) for the management of risk relating to housing development on dolomitic land are also presented.

INTRODUCTION

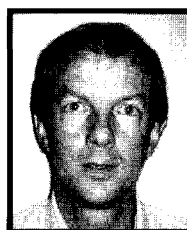
In South Africa, the term 'dolomite land' has a negative connotation due to its association with the damaging effects of sinkholes and dolines. The term is used for areas underlain directly or at shallow depth (<100 m) by dolomitic rock of the Chuniespoort Group of the Transvaal Supergroup (Proterozoic age). It therefore includes areas where dolomite is covered by younger deposits (Pretoria Group) of the Transvaal Supergroup, the Karoo Supergroup (Palaeozoic age) or unconsolidated deposits of Cenozoic age.

Twenty per cent of the densely populated Pretoria-Witwatersrand-Vereeniging area of Gauteng Province is underlain by dolomite (Van Schalkwyk 1981) and most of the gold mining areas in the Far West Rand and North-West Province occur on dolomite land. These areas are used extensively for urban and industrial development, and in the past forty years 38 people have lost their lives in sinkholes, while damage to or loss of property has exceeded R1 billion. Although damage to property continues to escalate, no loss of life in sinkholes has been reported since the early 1970s. Damage to property and loss of life have been recorded in rural and urban areas, including residential, commercial and industrial developments. In spite of this sad history, there is increasing pressure to provide more housing on dolomite, especially for underprivileged communities. It is the authors' opinion that most of the losses as a result of sinkholes and dolines can be attributed to inappropriately designed development on dolomite land and are avoidable.

Dolomitic rock is composed mainly of the mineral dolomite, which is a carbonate of calcium and magnesium. Groundwater that is weakly acidic through enrichment with carbon dioxide dissolves and removes the calcium and magnesium in the form of bicarbonates as it percolates through the network of joints, fractures and faults in the rock mass. This dissolution gives rise to karst features in the form of cave systems and voids. In many parts of South Africa the karst landscape is buried beneath younger deposits and/or weathering products of the dolomitic formation, and these materials can either collapse or be transported into voids or cave systems, resulting in catastrophic ground movement at surface. The manifestation of this movement is either a sinkhole or a doline (subsidence). Sinkholes are generally of limited areal extent (diameter <100 m), but can manifest within seconds and without warning. Dolines, on the

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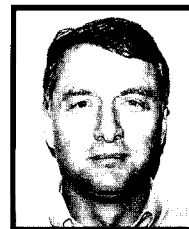


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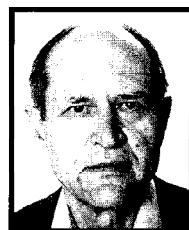
DAVE

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other hand, are large depressions, typically 30 m to 1 km in length, that develop slowly over periods of weeks, months or even years. More information on the mechanism of sinkhole and doline formation can be found in the literature, eg Enslin (1951), Brink and Partridge (1965), Kleywegt (1974), Kleywegt and Pike (1982), Buttrick and Van Schalkwyk (1995 and 1998) and Jennings, Brink, Louw and Gowan (1965).

Buttrick (1992) addressed the need for documenting a standardised, functional framework of reference for characterising the potential stability of sites on dolomitic land, and the Method of Scenario Supposition for evaluating the risk of sinkhole and doline formation was proposed by Buttrick and Van Schalkwyk (1995). This method requires hypothesising the impact of man's future activities on the risk for sinkhole and doline formation within a dolomitic karst environment in the context of either a dewatering or non-dewatering scenario.

With the more recent requirement (Section 12, Act 95 of 1998) that local authorities and other institutions adopt risk management systems, it is clear that dolomitic stability characterisation has to be refined further to include the concepts of both Hazard and Risk (Buttrick & Van Schalkwyk 1998). Although the terms hazard and risk are applied in a connotative sense in many fields of work, the authors decided to use them in the context of their literal and primary meaning. This was done after consultation with colleagues and technical members of the insurance industry (Carter 1999).

Legal requirements for geotechnical investigations of dolomite land for residential development have been incorporated in various Acts and Ordinances (Van Schalkwyk 1998) and are now also contained in the National Home Builders Registration Council's Home Building Manual (NHBRC 1999), a document published in terms of the Housing Consumers Protection Measures Act (Act 95 of 1998).

The Method of Scenario Supposition (Buttrick & Van Schalkwyk 1995) focuses on the planning stage of development rather than on the detailed development stage, and can therefore not solely be used to control housing design and development. In order to address this shortcoming, the Joint Structural Division of the South African Institution of Civil Engineering (1998) developed and published an addendum (Joint Structural Division 1998) to their Code of Practice (1995) on areas underlain by dolomites. This addendum provides for Dolomitic Area Designations by which housing sites can be described in terms of precautionary measures, similar to the way in which Site Classes are used to describe sites in terms of foundation design and building procedures (Watermeyer & Tromp 1992). The Home Building Manual (NHBRC 1999) contains a slightly modified version of the Dolomitic Area Designations and

requires that housing sites underlain by dolomites be designated both in terms of Dolomitic Area Designations and Site Classes. The Standard Method for Dolomitic Land Hazard and Risk Assessment presented in this paper integrates a modified version of the Method of Scenario Supposition with the Dolomitic Area Designations provided for in the Home Building Manual.

The contents of this paper are presented as part of ongoing consideration and research to enhance the quality of dolomite stability investigations. It should be viewed as a set of guidelines that must be applied with professional judgement, rather than a recipe that is prone to misuse in the hands of inexperienced practitioners. The authors intend to update these guidelines from time to time and would welcome suggestions for improvement from colleagues.

TERMINOLOGY AND DEFINITIONS

Hazard and risk

The Oxford and Collins dictionaries respectively define hazard as 'things that can cause damage' and 'a thing likely to cause injury'. These dictionaries respectively define risk as 'the possibility of meeting danger' and 'the possibility of incurring misfortune or loss', that is, the 'possibility' of the 'thing' happening. Technical members of the insurance industry indicate that risk is 'probable occurrence in a period of time' and hazard is defined as 'what dangers you may come up against which may cause damage/injury and can/cannot be avoided depending on the risk and risk factors'. They further indicate that where 'risks are high, more hazards will present themselves' (Carter 1999). Tietz (1998) indicates that the analysis of risk may in one case be scientifically and/or statistically based and, in another case, call on judgement, instinct or prejudice. In the context of the stability characterisation of sites on dolomite land, the following concepts and definitions are put forward:

- **Hazard:** Hazard refers to the feature (ie sinkhole or doline) that manifests and is determined by the characteristics of the dolomite profile. The scale of the hazard is expressed as small, medium, large and very large, for example medium-size sinkhole.
- **Inherent Risk:** Inherent Risk of a site refers to the chance for a certain size sinkhole or doline to occur within the postulated scenario of land use and dewatering or non-dewatering. It depends on the mobilising potential of the blanketing layer and the nature of the mobilising agents. Since the nature of the mobilising agents depends on the future land use and can usually not be assessed during the

site characterisation stage, it must be assumed that the site is developed and treated inappropriately, resulting in all mobilising agents becoming operative. To assess the Inherent Risk, one must assume that the mobilising agents are acting on the subsurface profile of a site. Inherent Risk is rated in three categories (low, medium or high) and a site (profile) retains its Inherent Risk irrespective of the recommended or actual development on surface.

- **Development Risk:** Development Risk refers to the likelihood and extent of loss of life, loss or damage to property, or financial loss and is rated in two categories, namely acceptable or unacceptable. The assessment of development risk is based on the Hazard, the Inherent Risk, the socio-economic factors (including type of development, density of development, level of servicing, precautionary and remedial measures and level of risk management) and time.

Factors for characterising Hazard and Inherent Risk

Postulated mechanisms of sinkhole and doline formation involve different processes, geological settings and agents. Current knowledge of the mechanisms of sinkhole and doline formation require that use should be made of a generalised and simple set of factors (circumstances, facts or influences contributing to a result) to evaluate the Hazard and Inherent Risk.

Terminology used for dolomite land Hazard and risk assessment is defined below. An idealised three-dimensional model of a portion of dolomite land is depicted in figure 1 on page 29. The various components of the model are used to assist in explaining the definitions.

- **Blanketing layer:** Dolomitic overburden comprises all the materials occurring between the ground surface and the dolomitic bedrock surface. It typically includes residual dolomitic soils (wad and chert rubble), fresh and weathered intrusive sills, layers of Karoo sedimentary rocks and Quaternary deposits. The term blanketing layer, however, is defined here as that component of the dolomitic overburden that overlies the potential receptacles. Figure 1 depicts two blanketing layers, one of which (1a) comprises the full thickness of dolomitic overburden, while the other (1b) is relatively thin and overlies interconnected openings within the overburden.
- **Receptacles:** Receptacles may occur either as small disseminated and interconnected openings in the overburden (especially where chert rubble is pres-

ent), or as substantial openings (cavities) in the bedrock. Both types of openings may be able to receive mobilised (transported) materials from overlying horizons.

- **Mobilisation and mobilising agents:**
In the dolomitic context, mobilisation is defined as the movement of dolomitic overburden by subsurface erosion. Mobilising agents include ingress water, ground vibrations, water level drawdown or any activity or process that can induce mobilisation of the material within the blanketing layer under the force of gravity. In a non-dewatering scenario the static ground water level is not an agent but a positive, mitigating factor.
- **Maximum potential development space:** The maximum potential development space is a simplified estimation of the maximum size sinkhole that can be expected to develop in a particular profile, provided that the available space is fully exploited by a mobilising agency (see figure 1). The available space depends on the depth below ground surface to the throat of a receptacle or disseminated receptacle and the 'angle-of-draw' in the various blanketing materials.

METHODOLOGY FOR DETERMINING THE HAZARD AND INHERENT RISK

Site investigation

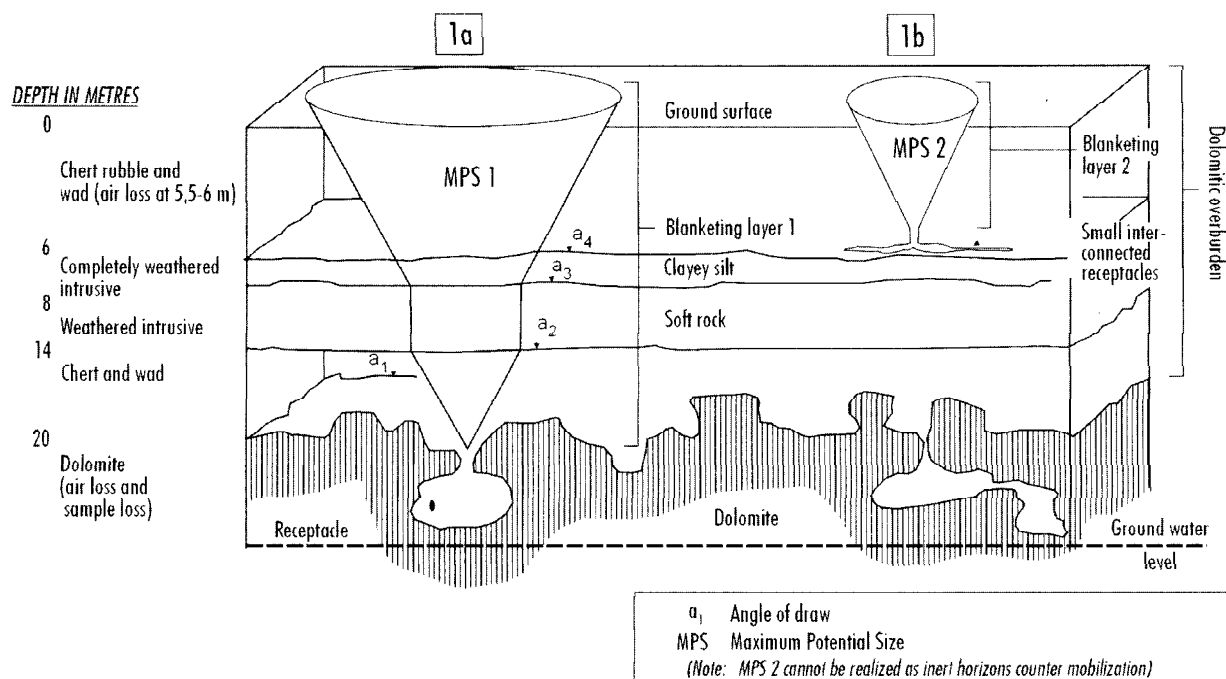
Geophysical surveys and/or relevant remote-sensing techniques and field information (geological mapping) are used to subdivide a site into potential (karst) morphological zones (steps 1 and 2, table 1).

Table 1 Application of the method of scenario supposition: some of the more important considerations

Step 1	Field reconnaissance and desk study of site	
Step 2	Preliminary zoning utilising tools such as air photo interpretation and geophysics	
Step 3	Preliminary boreholes to characterise 'preliminary' zonation	
Step 4	Characterisation process (scenario supposition). <i>Individual borehole profiles are reviewed within the context of the selected scenarios</i>	
	<i>Evaluation factors include inter alia</i>	
	<i>Sinkhole formation</i>	<i>Doline formation</i>
	Mobilisation agency/agents Receptacle development Potential development space (ie potential sinkhole size) Nature of blanketing layer/s Mobilisation potential of blanketing layer/s	Mobilising agency Nature of blanketing layer/s Mobilisation potential Lateral extent
Step 5	Pooling of individual borehole characterisations and amending of preliminary zoning, taking historical information into account. Individual boreholes and their risk characterisation represent point sources of data. Determine the lateral extent of the conditions providing the risk characterisation. The subsurface conditions represented by the various boreholes are used in conjunction with geophysical data, karst and bedrock morphology and geohydrology to determine the boundaries of areas of similar geotechnical characteristics and to develop a 'composite' Inherent Risk characterisation	
Step 6	Finalised risk zonation characterised in terms of a certain risk of certain sized features forming	
Step 7	Selection of appropriate development types and precautionary measures	
Step 8	Implementation of appropriate development design and precautionary measures	
Step 9	Ongoing risk management including vigilance and maintenance	

Boreholes are then drilled to characterise these zones in terms of Hazard and Inherent Risk (steps 3 and 4, table 1). After the characterisation of individual boreholes, all boreholes are viewed spatially through use of geophysical tools such as gravity. This can be done by

compiling isopach maps (horizon thicknesses, thickness of compressible materials, depth to bedrock, etc) and by extrapolation, thus providing information to refine potential stability zones and boundaries (step 5, table 1).



Determination of the Hazard

Sinkhole size

The maximum size of a sinkhole can be assessed by estimating the potential development space within the blanketing layer. This space is associated with either a receptacle or disseminated receptacles and depends on the following properties of the soil profile:

- Estimated depth below ground surface to the potential throat of either the receptacle or disseminated receptacles (ie the thickness of the blanketing layer).
- Size of the throat or potential throat. The size of the throat or potential throat may relate to the width of a solution opening (grike or fissure).
- Estimated 'angle of draw' in the various horizons of the blanketing layer. The 'angle of draw' in a material describes a cone and defines the angle of a metastable slope to which a particular mobilising agency will become operative in that material. The material within the cone can potentially be mobilised by being moved or drawn into the conduit at the base of the cone. Typical angles of draw may range from 45 degrees for silty clay (wad) to 90 degrees for shale or chert. These figures are cited merely as examples of the range of values for the angle of draw. The values are dependent on local conditions, observation of actual sinkhole side walls in the immediate area, if available, and, more importantly, geotechnical information gathered during field investigation. Rigid values cannot be prescribed because of the variability of materials and the need to evaluate local conditions and apply professional judgement.

The first step in assessing the potential development space is to consider the presence of receptacles or disseminated receptacles. Any suppositions made should be elaborated on in the reporting stage of an investigation giving reasons based on experience and data.

Conservative assumptions should be reported. For example, it may be assumed that receptacles are present within the bedrock, although not encountered during drilling.

The second step is to determine the depth below ground surface of the potential receptacles. The presence of disseminated receptacles occurring above the dolomitic bedrock should also be considered. It may be necessary to assess or accept the worst possible situation.

The third step is to consider the thickness of the various horizons constituting the blanketing layer. Figure 1 displays this concept schematically. The depth to the potential receptacle is obtained from borehole information, while the radius of the potential development space on surface is obtained by a simplified diagrammatic construction. The 'angle of draw' of the various materials and the depth of the receptacle are used to project and estimate the radius.

The size of the receptacles will determine to what extent the potential development space can be utilised. Thus for each receptacle there is a 'potential development space' that may be fully realised or exploited, creating the maximum size sinkhole, provided that (i) the receptacle is large enough to accommodate all the mobilised material from the potential development space, (ii) all the materials within the blanketing layer can be mobilised and (iii) an adequate and sustained mobilising agency is present. As there is no efficient technique available at present to ascertain the volume of receptacles, it must be assumed that receptacles of adequate volume are present.

Table 2 contains broad categories of 'potential development space' and hence the associated scale of potential maximum size sinkholes.

Doline size

Doline size is predictable only if formed by the process of premature termination of sinkhole formation. Where a doline is formed by consolidation of overburden material due to dewatering, the size is difficult to determine. However, the use of gravity and borehole data may give an indication of potential doline scale. Typical sizes range from several metres in width and length to several kilometres in

length. Consequently, for dolines, the intention is only to determine whether their formation is feasible and not to determine their sizes. Hazard is therefore typically expressed as 'doline and large sinkhole' or 'doline and medium-size sinkhole'.

Determination of the Inherent Risk

Sinkholes

The Inherent Risk for sinkhole formation is a reflection of the geotechnical characteristics of the materials in the blanketing layer and depends mainly on the susceptibility (also termed mobilising potential) of materials to exploitation and mobilisation under the influence of a mobilising agency.

For the selection of this hypothetical mobilising agency, it is assumed that the site will be 'abused' through inappropriate land use, poor management of stormwater and waterbearing infrastructure during future development and the worst-case scenario for dewatering and/or water ingress should be assumed.

The susceptibility of the blanketing layer to mobilisation and formation of a sinkhole is expressed in terms of risk that is classified as a Low, Medium or High Inherent Risk. The Inherent Risk of a site remains the same, irrespective of the recommended or actual development type.

The first step is to consider the potential mobilising agents. In the evaluation and reporting procedure, it is important to indicate clearly the particular external mobilising agents or combination of agents to which the blanketing layer may be subjected in future. Substantiation should be provided for assumptions made in the deductive process.

The next step is to consider the mobilising potential of the blanketing layer. Boreholes drilled during a site investigation are individually evaluated and their profiles characterised by being abstractly subjected to the activity of an assumed mobilising agency within the context of the selected scenario. This borehole information is also considered in conjunction with geophysical information. Kleywegt and Enslin (1973) described the use of gravity as a tool in delineating potentially problematic areas with respect to ground settlement. If, for example, it is assumed that the profile will be subjected to a mobilising agency in the form of ingress water, then the potential susceptibility to erosion of the materials within the blanketing layer must be assessed. The susceptibility to consolidation and subsurface erosion, including piping erosion, should be carefully argued, considering aspects such as the grading, density and permeability. If it is likely that dewatering of the local dolomite aquifer will occur during the lifetime of the development, then the dewatering scenario must be considered. In a non-dewatering situation, where sub-

Table 2 Suggested scale of sinkhole sizes (the Hazard) (Buttrick & Van Schalkwyk 1995)

Maximum potential development space	Maximum diameter of surface manifestation (dimension: metres)	Suggested terminology
Small potential development space	<2	Small sinkhole
Medium potential development space	2-5	Medium-size sinkhole
Large potential development space	5-15	Large sinkhole
Very large potential development space	>15	Very large sinkhole

Table 3 Guidelines for assessing the risk for mobilisation of the blanketing layer (Inherent Risk for sinkholes)

Inherent Risk	Typical site conditions
Low	The profile displays no voids. No air loss or sample loss is recorded during drilling operations. Either a very shallow water table or a substantial horizon of materials with a low potential susceptibility to mobilisation may be present within the blanketing layer (eg continuous intrusive features or shale material). Depth to potential receptacle is typically great and the nature of the blanketing layer is not conducive to mobilisation
Medium	This type of profile is characterised by an absence of substantial 'protective' horizon and has a blanketing layer of <i>materials potentially susceptible to mobilisation</i> by extraneous mobilisation agents. The water table is below the blanketing layer
High	The blanketing layer of the high-risk profile reflects a great susceptibility to mobilisation. A void may be present and is interpreted to be very likely, within the potential development space, indicating that the process of sinkhole formation has already started. Boreholes may register large cavities, sample loss, air loss, etc. Convincing evidence exists of cavernous sub-surface conditions which will act as receptacles. The water table is below the blanketing layer. In a dewatering situation, the lowering of a shallow groundwater level would obviously increase the risk of mobilisation

surface erosion is caused by ingress water, the premature termination of the process may result in a doline rather than a sinkhole. The mobilisation potential is evaluated in terms of different scenarios or the interaction of various scenarios.

The characterisations of the individual boreholes within a potential zone are then considered collectively (step 5, table 1). If several boreholes confirm a particular Inherent Risk characterisation, that zone will be defined accordingly. The sub-surface conditions represented by the various boreholes are used in conjunction with geophysical data, anticipated karst and dolomite bedrock morphology and geohydrology to develop a holistic perspective of a subarea and a 'composite' Inherent Risk characterisation of the zone. If there are marked deviations, the zoning should be modified by the creation of separate zones, always erring in the favour of a conservative (worst-case) assessment.

The susceptibility of the subsurface profile, and in particular the blanketing layer to mobilisation, is described in table 3.

MPS1 (Maximum anticipated potential development space) in figure 1(a) depicts a profile with a deep groundwater level situated within the bedrock. The blanketing layer and hence the potential development space is fully exposed to the potential activities of extraneous mobilising agents. This figure also depicts a significant layer of intrusive material with a low mobilisation potential, that is, Low Inherent Risk. This horizon acts as either an aquitard or an aquiclude that prevents mobilisation and movement of materials into the receptacle. The material within the development space is thus protected from the mobilisation agency.

MPS2 (Maximum anticipated potential development space) in figure 1(b) reveals the presence of potential disseminated receptacles above the intrusive horizon displaying the low mobilisation potential, that is, Low Inherent Risk. A smaller potential development space is

thus available for exploitation by a mobilising agency.

Dolines

The susceptibility of the soil material to mobilisation, that is, consolidation settlement under the influence of the mobilising agency (water table drawdown or surface water ingress), may be characterised as described in table 4.

Establishing the Development Risk

Urban development normally results in a disturbance of the metastable conditions prevalent in the dolomitic environment. Consequently, the basic design of a township is a key element in the overall strategy to minimise the impact of the proposed development. For example, the placement of a high-density site and service scheme on an area characterised as of high Inherent Risk for medium-size sinkhole development is not good practice and must not be allowed. Such development is less controlled, services of inferior quality may be utilised, and there may not be the necessary control on surface drainage. If a catastrophic event were to occur, the high population concentration

Table 4 Guidelines for assessing the risk for mobilisation of the blanketing layer (Inherent Risk for dolines)

Inherent Risk	Typical site conditions
Low	In this type of profile, the water table can be (i) above the bedrock and at shallow depth reducing the likelihood of ingress water eroding the blanket layer, (ii) in the dolomite bedrock negating the effect of water table drawdown or (iii) in soil material with geotechnical characteristics reflecting a low susceptibility to consolidation settlement, ie material with high density, low void ratio and low compression index (eg Karoo shale)
Medium	This type of profile is characterised by an absence of a substantial 'protective' horizon and has a blanketing layer of materials potentially susceptible to mobilization by ingress water. The water table is within the bedrock or at depth within the blanketing layer. Voids and disseminated voids may be present above the bedrock, indicating the susceptibility to doline formation

Table 5 Inherent risk characterisation and anticipated number of ground-movement events

Inherent Risk characterisation	Ground-movement events per hectare in a 20-year period after an initial 20-year period (statistics based on inappropriate and poor service design)
Low	$0 \leq 0,1$
Medium	$> 0,1 \leq 1,0$
High	$> 1,0$

dramatically increases the likelihood of people losing their lives. The Development Risk is therefore unacceptable. An area with such a Hazard and Inherent Risk characterisation could be better utilised for commercial or light industrial development where more elaborate and expensive design solutions can be afforded to reduce the likelihood of disturbing the metastable state and hence making the Development Risk acceptable.

Once the Hazard and Inherent Risk of a site have been established, a type of development can be selected that is appropriate and will result in an acceptable Development Risk over a specified period of time.

Table 5 indicates the number of ground-movement events anticipated to be generated in low, medium and high Inherent risk areas if inappropriate development were to take place.

Acceptable Development Risk

Development Risk is regarded as 'acceptable' where the statistical occurrence of events is in the range of $0 \leq 0,1$ event per hectare over a twenty year period (preferably at the lower end of the scale) and 'unacceptable' where the number of events exceeds 0,1 event per hectare. In relating this limit to the established Inherent Risk of a site, it must be kept in mind that the definition of Inherent Risk implies inappropriate use of the site.

Experience shows that sites of Low and Medium Inherent Risk (< 1 event per hectare) may be considered for residential development, since the Development Risk

can be maintained at an 'acceptable' level through appropriate township design, remedial measures, precautionary measures, vigilance and proactive maintenance strategies. Similarly, sites of High Inherent Risk may be used for selected industrial and commercial development through the use of appropriate design and maintenance measures such as extensive paving around structures, extensive stormwater systems, and lower density of waterbearing infrastructure.

RISK CHARACTERISATION AND APPROPRIATE URBAN DEVELOPMENT

It is recommended that use be made of a zoning system relating the Inherent Risk

characterisation of an area and certain suitable or appropriate types of development. Table 6 denotes these suggested types of development as related to the Inherent Risk and the Hazard characterisation. Development design is based on the most conservative assessment for an area, that is, on the risk of the most catastrophic events occurring.

The recommendations are a systematic progression of measures:

- Limited restriction on the type of residential development, provided that certain precautions are taken in the design and maintenance of services.
- Restrictions that affect both the density of development and the type of development, for example making

provision for structures where the additional costs of special foundations and precautions can be afforded.

- Recommendations that land allocation be restricted to open areas or special parks.

The basic philosophy of this zoning system is therefore that with increasing Inherent Risk of more catastrophic events occurring, the density of development should decrease and construction costs would increase, that is, the Development Risk must remain 'acceptable'.

Table 6 does not deal with all the possible combinations of Inherent Risks and events, but does indicate development type as related to a trend of 'increasing

Table 6 Characterisation: Inherent Risk of doline and a specified-size sinkhole forming (Hazard)

Inherent Risk Class	Small sinkhole	Medium sinkhole	Large sinkhole	Very large sinkhole	Risk of doline formation	Recommended type of development in order to maintain acceptable Development Risk
<i>Sinkhole diameter</i>	< 2 m	2–5 m	5–15 m	> 15 m		
Class 1	Low	Low	Low	Low	Low #NDS or DS	Residential, light industrial and commercial development provided that appropriate water precautionary measures are applied. Other factors affecting economic viability such as excavatability, problem soils, etc, must be evaluated
Class 2	Medium	Low	Low	Low	Medium #NDS	Residential development with remedial water precautionary measures. No site and service schemes. May consider for commercial or light industrial development
Class 3	Medium	Medium	Low	Low	Medium #NDS	Selected residential development with exceptionally stringent precautionary measures and design criteria. No site and service schemes. May consider for commercial or light (dry) industrial development with appropriate precautionary measures
Class 4	Medium	Medium	Medium	Low	Medium #NDS	Selected residential development with exceptionally stringent precautionary measures and design criteria. No site and service schemes. May utilise for commercial or light (dry) industrial development with appropriate stringent precautionary measures
Class 5	High	Low	Low	Low	High #NDS	These areas are usually not recommended for residential development but under certain circumstances selected residential development (including lower-density residential development, multi-storied complexes, etc), may be considered, commercial and light industrial development. The risk of sinkhole and doline formation is adjudged to be such that precautionary measures, in addition to those pertaining to the prevention of concentrated ingress of water into the ground are required to permit the construction of housing units
Class 6	High	High	Low	Low	High #NDS	These areas are usually not recommended for residential development but under certain circumstances highrise structures or gentleman's estates (stands 4 000 m ² with 500 m ² proven suitable for placing a house) may be considered, commercial or light industrial development. Expensive foundation designs may be necessary. Sealing of surfaces, earth mattresses, water in sleeves or in ducts, etc
Class 7	High	High	High	Low	High #NDS	No residential development. Special types of commercial or light industrial (dry) development only (eg bus or trucking depots, coal yards, parking areas). All surfaces sealed. Suitable for parkland
Class 8	High	High	High	High	Low–High *NDS or DS	No development, nature reserves or parkland

* = Number of anticipated events per hectare over a period of 20 years with poor design and management (see table 3).

= Non-Dewatering Scenario and Dewatering Scenario.

Table 7 Dolomitic area designations (Joint Structural Division 1998; NHBRC 1999)

Dolomitic Area Class	Description	Typical foundation solutions (masonry structures)
D1	No precautionary measures are required to permit the construction of housing units due to an adequate overburden thickness	Foundations in accordance with the Joint Structural Division's Code of Practice (1995)
D2	The risk of sinkhole and doline formation is adjudged to be such that only general precautionary measures , which are intended to prevent the concentrated ingress of water into the ground, are required to permit the construction of housing units	Foundations in accordance with Joint Structural Division's Code of Practice (1995)
D3	The risk of sinkhole and doline formation is adjudged to be such that precautionary measures in addition to those pertaining to the prevention of concentrated ingress of water into the ground, are required to permit the construction of housing units	<p>Possible solutions where sinkholes occur include the provision of</p> <ul style="list-style-type: none"> • reinforced concrete grids between exposed pinnacles (Wagener 1985) • mattresses of improved material (Wagener 1985) • raft foundations to allow occupants to escape and limit damage in the event of a sinkhole occurring (JSD 2000) <p>Possible solutions where dolines are expected include split construction and raft construction in accordance with the Joint Structural Division's Code of Practice (1995)</p>
D4	The risk of sinkhole and doline formation is such that precautionary measures cannot adequately reduce such risks to acceptable limits so as to permit the construction of housing units or the precautionary measures which are required are impracticable to implement	

Table 8 Some relationships between Dolomite Risk classes and NHBRC area designations

Dolomite Risk Class	Selection of ranges of potential alternative Dolomite Area Designations
Class 1	D2
Class 2	D2
Class 3	D2 or D3 depending on subsurface conditions or stand densities
Class 4	D2 or D3 depending on subsurface conditions or stand densities
Class 5	D3 or D4
Class 6	D4
Class 7	D4
Class 8	D4

Inherent Risk of increasingly catastrophic (hazards) events', and enables decisions to be taken regarding the type of development which may take place.

If, for example, an area is characterised as reflecting a high Inherent Risk of small sinkhole formation and a low Inherent Risk of larger features developing, it is designated as Class 5 (table 6). The interpretation of geotechnical conditions leads to the conclusion that a preponderance of small-size sinkholes are anticipated, should events be triggered. However, this designation does not exclude sinkholes of a larger scale forming, although they are regarded as less likely. It should be borne in mind that statistically a low Inherent Risk implies

an anticipated $0 \leq 0,1$ events per hectare over a 20-year period (table 2). Therefore, the worst-case scenario for the Class 5 area is interpreted as a high Inherent Risk for small sinkholes (ie more than 1,0 event per hectare per 20-years may be anticipated without risk management) and a low Inherent Risk (ie $0 \leq 0,1$ events per hectare per 20 years) for the various larger-size sinkholes.

Where conditions are characterised as reflecting a high risk of larger sinkholes forming, it is usually assumed that the risk is also high for the smaller sinkholes, except in exceptional geological settings. As an example, Class 6 represents conditions indicating a high Inherent Risk for medium-size sinkhole formation. Typically

the risk of the smaller sinkholes is also high, since the susceptibility to mobilisation of the profile is the same for both small and medium-size sinkholes.

Where residential development type and stand size are known, townships can be classified in terms of the Dolomitic Area Designations set out in table 7. Individual stands can be classified as being Class P (dolomitic) sites. The near surface soil horizons can be classified in terms of table 2.1 of the Joint Structural Division Code of Practice (1995) as being R, C, C1, C2, H, H1, H2, H3, S, S1 or S2. The site class of a particular stand should for example be described as Class P (dolomitic-D2/C2)

The relationship between table 6 and table 7 is set out in table 8, while minimum and mandatory remedial measures for areas designated as being D2 and D3 are given in Appendix A (JSD 1998).

NHBRC REQUIREMENTS FOR SITES UNDERLAIN BY DOLOMITE

The Housing Consumer Protection Measures Act (Act 95 of 1998) provides, inter alia, for warranty protection against defects in new homes and the establishment of technical standards in, and the regulation of, the home building industry. This Act in effect requires that all contractor-built housing in South Africa be built by home builders who are registered with the National Home Builders Registration Council and in accordance with the Home Building Manual of the NHBRC. The Act also requires that home loans by financial institutions and housing subsidies by provincial housing boards are only made to housing consumers if the home builder is registered with the NHBRC and the home is or will be enrolled with the NHBRC.

The Act provides for a fine of an amount not exceeding R25 000 or imprisonment of up to a year in respect of every director, trustee, managing member or officer of a home builder who knowingly permits a contravention of the Act in respect of each charge.

The NHBRC's Home Building Manual (1999) requires that home builders appoint Competent Persons to establish the risk of sinkhole and doline formation

... in townships or portions thereof which are directly underlain by dolomites or limestones, ie at the surface or covered by surficial rocks measured on the gravity highs (eg Karoo Supergroup, Pretoria Group rock and their intrusives) of depth less than:

- 30 metres in areas underlain by lime stones
- 60 metres in areas underlain by dolomites where no de-watering has taken place and the local authority has jurisdiction, is monitoring and

has control over the groundwater levels over the areas under consideration

- 100 metres in areas underlain by dolomite where de-watering has taken place or where the local authority has not jurisdiction or control over ground water levels

Where the surficial rocks are thicker than the required minimum, specific attention should be paid to delineate dolines within which differential settlement has occurred or is likely to occur. In areas overlain by the Pretoria Group, attention should be paid to the possible presence of faults as sinkholes are known to occur along such geological features. Care shall be taken to identify palaeosinkholes, as the construction of housing units above such formations is prohibited.

Areas underlain by dolomites and limestones should be designated in accordance with table 7 based on the classification in table 6 and the relationship in table 8. Services in areas designated as being D2 and D3 are required to be installed in accordance with the guidelines given in Appendix A. Measures to address risks associated with sinkhole formation in areas designated as D3 should include the provision of reinforced concrete grids spanning between exposed pinnacles (Wagener 1985), the provision of mattresses of improved material (Wagener 1985) and the provision of raft foundations to enable the housing unit to span over a sinkhole to allow occupants to escape from the unit and to limit structural damage after the occurrence of a sinkhole (JSD 2000).

The Competent Person is required to liaise with the local authority under whose jurisdiction the proposed township lies and to include, in his submission to the NHBRC, a statement by such authority on their services risk management systems in dolomitic or limestone areas. Such statements must be signed by the relevant chief executive officer and include the authority's policy and procedures which it has in place in respect of the installation of bulk water and sewer services, measures to prevent land invasion on areas zoned as D4, maintenance of township services, and enforcement of any special provisions and/or restrictions which may be imposed on individual erven. In sectional title developments, the home builder is also required to prepare and submit a services risk management plan, acceptable to the NHBRC, for inclusion in the constitution of the body corporate which is to be established, together with a firm undertaking that this plan be incorporated in the constitution which is put before the first body corporate meeting for adoption (NHBRC 1999). Matters which need to be considered when establishing and maintaining a risk management system are set out in Appendix B.

The NHBRC will only enrol housing

units constructed in areas underlain by dolomites/limestones falling within areas demarcated as being Designation D1, Designation D2 or Designation D3 upon recommendation from its Technical Advisory Group. Its standing procedures in this regard are as follows (NHBRC 1999):

- The home builder must submit to the NHBRC a duly completed form countersigned by the Council for Geoscience, together with the local authority's risk management statement, duly signed by their chief executive officer, and a report detailing the investigations undertaken and the basis upon which the zone designations are arrived at and, where relevant, a sanitation and stormwater plan.
- The home builder and his 'Competent Persons' may be required to make a presentation to the Technical Advisory Group.
- The Technical Advisory Group subjects the report and the sanitation and stormwater plans, if any, to a peer review, confirm or advises of amendments to the zoning and advise the NHBRC of their risk exposure in respect of the application.
- The NHBRC, upon advice of the Technical Advisory Group, decides in principle whether or not to enrol sites within the township, or portion thereof, on an individual site basis or to deny enrolment from the outset of some or all of the sites.

CONCLUSIONS

Dolomitic land occupies significant portions of densely populated areas in Gauteng and in some areas of the North-West Province, where there is an urgent need for additional housing for, inter alia, the poorest sector of the economy. However, dolomitic terrain is known for the occurrence of catastrophic sinkholes and dolines, especially in areas where the metastable subsurface conditions have been disturbed by man's activities.

The urgent need for a standard method to assess the Inherent Risk of a certain type of event (size of sinkhole or doline – hazard) occurring in an area that has been (or is expected to be) exposed to a specific type of human 'abuse' has led to the refinement of the 'Method of Scenario Supposition' and development of the Proposed Method for Dolomite Land Hazard and Risk Assessment presented in this paper.

This method allows the site geological conditions to be evaluated by means of well-defined factors based on the known mechanisms of sinkhole or subsidence formation and, in the case of housing developments enables risk to be managed in accordance with the provisions of the Housing Consumers Protection Measures Act. This methodology is not prescriptive, but provides a deductive framework that

requires professional judgement, based on the results of geotechnical investigation.

The final characterisation of an area provides the Inherent Risk of a certain Hazard occurring, ie doline and specific-size sinkhole formation. Based on the Inherent Risk and the Hazard, appropriate township design, water precautionary and remedial measures and ongoing risk management can be implemented to ensure that the Development Risk is and remains acceptable. In this manner sustainable development is ensured.

It should be emphasised that the Proposed Method for Dolomite Land Hazard and Risk Assessment and the Dolomite Area Classes constitute a clear channel of communication between the geotechnical and structural engineering professions, between professionals and building control officers, and between professionals and developers.

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APPENDIX A

Minimum requirements and mandatory precautionary measures in areas underlain by dolomites

The Joint Structural Division established the following minimum requirements and mandatory precautionary measures for areas designated as being D2 and D3. These minimum and mandatory precautionary measures have been adopted by the NHBRC in their Home Building Manual.

General

- 1 The site and surrounding area shall be shaped to permit the ready drainage of surface water and to prevent ponding. *Drainage ports should be incorporated in boundary walls particularly at the lowest point of the site, to permit the passage of surface runoff.*
- 2 Natural ponds and water courses located within 10 m of any structure shall be rendered impervious.
- 3 Sanitation systems shall not incorporate soak aways.
- 4 Backwash and other water from swimming pools shall be discharged into either the storm water or drainage systems as required by the local authority. *The dolomitic stability over the route of any bulk water bearing service should be evaluated.*

Township services

- 5 Underground services shall be designed and constructed so as to minimise maintenance requirements and any potential leakage points in wet services and shall, as far as possible, be designed to avoid possible disturbance of the underground environment.
- 6 The relevant provision of SABS 1200 DB, L, LB, LC, LD and LE shall be

observed in the installation of all underground services.

- 7 The backfilling to service trenches and other excavations shall, except in rock, not be more permeable than the surrounding material.
- 8 The stormwater drainage and sewerage system shall incorporate measures to ensure watertightness of conduits and other compartments. Whenever possible, storm water should be channelled in lined, surface canals. *Concrete non-pressure pipes should be of the spigot and socket type with rubber ring seals. Joints in box culverts, channels, etc, should be sealed.*
- 9 Storm water drainage conduits shall be constructed at gradients, which will not permit the deposition of silt, or sand, of the type present in the catchment area.
- 10 Water mains shall be laid only in road reserves.
- 11 Water piping materials shall be one or more of the following:

pipes of 75 mm and larger diameter:
high impact PVC pipes with
vitaualic joints

steel pipes with internal and external corrosion protection or other flexible (as defined in SABS 0102 Part 1) water pipes with flexible, self anchoring connections

pipes having a diameter of less than 75 mm:

HDPE type IV piping
polypropylene piping

The piping used in mains and communication pipes should be flexible, joints should be minimal in number and, be of the flexible, self-anchoring type, ie not reliant on thrust blocks or friction for their anchorage.

- 12 Provision for future connections shall be made in order to minimise the cutting into pipes to provide such connections.
- 13 Provision shall be made in all water bearing pipelines to accommodate any potential differential movements without causing the pipeline or joints to leak.
- 14 Road surfaces shall be located sufficiently low so as to permit the drainage of erven onto them.
- 15 Roadways which have a gradient of less than 1:80 shall be surfaced/sealed.
- 16 Where un-surfaced roads are the sole storm water system in a township, the roadways which act as major storm water collectors shall be surfaced.
- 17 The velocity of the 1 in 20 year storm water flowing along unsurfaced roadways shall not exceed 1,5 m/s.

Plumbing

- 18 Water pipe entries into the buildings shall be in accordance with Figure S3.

- 19 All sewer and water pipes and fittings shall be provided with flexible, water-tight joints.
- 20 No plumbing and drainage pipes shall be placed under floor slabs, as far as is practicable.
- 21 The fall of the trenches shall be away from the buildings.
- 22 Pipes through walls shall be sleeved to permit relative movement.
- 23 WC pans shall be provided with a flexible connection at the junction with the outlet pipe.
- 24 The selection of piping material shall take cognisance of corrosion (both external and internal).
- 25 Water pipes shall have a minimum cover of 500 mm.
26. Wherever practical, service trenches shall not be excavated along the length of housing units within the first 3,0 m beyond the perimeter of such units.

Site precautions

- 27 Down pipes, if provided, shall discharge into concrete line drainage channels which discharge the water at least 1,5 m away from buildings.
- 28 Where guttering is not provided, a 1,5 m wide impervious apron slab shall be provided.
- 29 The ground immediately against the buildings shall be shaped to fall in excess of 75 mm over the first 1,5 m beyond the perimeter of the building, from where it shall drain freely away from housing units. Apron slabs, where provided, shall have the same fall.

APPENDIX B

Matters to be considered when establishing and maintaining a Risk Management System

1 New townships

- 1.1 Bulk and internal services in new townships must be installed in accordance with the provisions of Appendix A and any additional provisions provided in the geotechnical report.
- 1.2 A register of townships in areas designated as being D1, D2, D3 and D4 (Risk Classes 1 to 8I) should be opened. Specified precautionary measures should be entered into the register where they differ from the minimum requirements set out in Appendix A.
- 1.3 The local authority must ensure that bulk services are upgraded appropriately in relation to increasing residential densification.

2 Raising awareness

- 2.1. A map of all known dolomite areas within the local authorities area of jurisdiction should be prepared and maintained. This map should provide a composite stability zonation based on the Dolomite Area Designations and the related Dolomite Risk Class, eg D2 (Risk Class 1) and D3 (Risk Class 5). The Dolomite Area Designation will be of immediate importance to civil engineers involved in service design and maintenance, whereas the Dolomite Risk Class will be of value to the dolomite risk specialists from a development perspective.
- 2.2 The sections/departments of local authorities responsible for the maintenance of the water, sewer and electrical reticulation and bulk services as well as the building control section should be issued with maps showing the D2, D3 and D4 (Risk Classes 1 to 8) areas and must be informed of the potential risks and maintenance requirements for services in these areas.
- 2.3 Councillors whose wards fall within D1, D2, D3 and D4 (Dolomite Risk Class 1 to 8) areas, as well as leaders of community structures and organisations whose constituents reside in D2 (Classes 1 to 4) and D3 (Classes 3 to 5) areas, should be informed of the potential risks and maintenance requirements for services in these areas and the necessity to report any leakage/blockages/ponding of water in these areas to designated council officials.
- 2.4 Officials who receive and log reports from the public on disruptions in services, etc, must be provided with contingency plans including maps showing D2 (Classes 1 to 5), D3 (Classes 3 to 5) and D4 (Classes 6 to 8) areas and must be briefed on the implications of leaks and the like in these areas. Special reporting procedures must be established to ensure that maintenance teams are promptly advised of leaks and the like in areas designated as being D2, D3 and D4.
- 2.5 The local authority should inform residents in areas designated D2 (Classes 1 to 5) and D3 (Classes 3 to 5), every two years in a written communication, of the risks and their responsibilities which will include:
 - prompt reporting of leaks and any subsidence
 - refraining from making illegal connections and proceeding with the erection of new buildings on properties and the installation of swimming pools without permission
 - ensuring that water does not dam up on their properties

3 Maintenance of services

- 3.1 A proactive maintenance strategy for waterbearing infrastructure should be developed. This can be readily done by superimposing the waterbearing infrastructure on the stability risk zonation map described in Section 2.1 above. Priority in terms of vigilance, general maintenance, repair of leaks and expenditure of funds for upgrading or service replacement can be assigned on the basis of risk exposure. In this manner a prioritised, co-ordinated and pro-active strategy for maintenance and review of waterbearing infrastructure can be developed by the local authority.
- 3.2 Areas designated as being D2, D3 and D4 (Dolomite Risk Classes 1 to 8) must receive priority in the repair of leaks arising from the sewer and water reticulation.
- 3.3 Sewer mains in areas designated as D2, D3 or D4 (Dolomite Risk Classes 1 to 8) should be checked for water tightness by means of an air test at intervals not exceeding two years and repairs undertaken where necessary.
- 3.4 The stormwater systems in areas designated as being D2, D3 or D4 (Risk Classes 1 to 8) should be inspected for blockages and leaks at intervals not exceeding one year and repairs/cleaning undertaken where required.
- 3.5 All bulk services which are located in areas designated as being D2, D3 and D4 should be inspected for water tightness/blockages at intervals not exceeding one year and cleared/repared where required.
- 3.6 Priority should be given to the upgrading of services in areas designated as being D2, D3 and D4 in order to minimise sewer overflows, ponding of water, bursts, water losses, etc.

4 Management of improvements to properties

- 4.1 Building control officers must, in areas designated as being D2 and D3, enforce any restriction regarding swimming pools and must ensure that alterations and additions are in accordance with the NHBRC requirements.
- 4.2 Building control officers should once every two years visually inspect properties in areas designated as being D2 and D3 to ensure that water is not damming up on properties.
- 4.3 Building control officers must not permit any densification of properties in areas designated as being D1, D2 or D3 unless it is confirmed by a

Competent Person that such densification does not change the area designation.

5 Measures to prevent land invasion

The local authority must put in place a policy and measures to preclude land invasions and to act positively where such invasions have occurred.

6 Groundwater control measures

Artificially induced fluctuations in the dolomite ground water level, particularly where shallow, may trigger sinkhole or doline formation. Consequently, it is essential that local authorities liaise with the Department of Water Affairs and set up appropriate groundwater monitoring procedures. Depending on the Dolomite Risk Class and Dolomite Area Designation (eg D4 or Class 7 and 8) of an area, in certain sensitive groundwater compartments, an outright ban on the sinking of abstraction boreholes may be required.

7 Emergency reaction plan in the event of a sinkhole or doline occurring

The local authority should set in place an emergency reaction plan to be followed in the event of a sinkhole or doline occurring in their area of jurisdiction. Managers of emergency services should be provided with the dolomitic zone designation and risk map and briefed on the implications thereof. It is essential that these managers and emergency services personnel fully understand what a sinkhole is, possible stages of development and how large an area to evacuate around a potential event.

8 Database of ground subsidence events and structural damage

The local authority should establish a database of ground subsidence events and reported structural damage. Detailed records of this nature are useful in developing a clear perspective of the stability situation in a township, highlight areas of weakness and assists in the installation and management of a proactive maintenance strategy.

Note

The policy should not cause residents to be concerned to live in dolomitic areas. It is perfectly safe to do so provided that certain precautionary measures are observed.

Discussion

Proposed method for dolomite land hazard and risk assessment in South Africa

D B Buttrick (Visitor), A van Schalkwyk (Visitor), R J Kleywegt (Visitor),
R B Watermeyer (Fellow) in *Journal of the South African Institution of
Civil Engineering*, 43(2) 2001:27–36

N Trollip, Engineering Geologist – Dolomite Stability Unit, Council for Geoscience:

One of the greatest benefits to come out of the introduction of the National Home Builders Registration Council (NHBRC) is the interaction between the various professionals resulting from the need to ensure acceptable development risk on dolomite. This interaction has been lacking for years, perhaps because (engineering) geologists and (structural and civil) engineers do not always speak a common language. As an aside: of particular concern is the fact that more universities are moving away from making insight into geology a prerequisite for engineering students, a move which is most certainly to lead to even further 'communication shortfalls'.

For the past 40 years, the Council for Geoscience (CGS) has played a role in ensuring that residential development on dolomite has been properly planned so that the integrity of the subsurface materials are not negatively affected and that its condition is maintained in perpetuity. This function has been rather one-sided in that a geological report was produced, the CGS commented on the dolomite related risk, recom-

mendations were made and the CGS report comment then represented the end of the line with regards to geologically related input. There was no coordinated inter-action between the planners, developer, engineers, local councils and the CGS before, during and after construction. Since 1 December 1999 this has changed dramatically.

The NHBRC procedure, contained in the Home Building Manual, now ensures the involvement of the engineering geologist right up to the construction (completion) phase. This added exposure (of the geologist and the CGS) to development has certainly presented many eye-openers, the most significant being the misconceptions regarding dolomite risk on the part of some engineers and the functions of the foundation types on the part of some geologists. Although some professionals are more than capable in the other discipline, many professionals fail to interact adequately. This has been borne out most prominently by engineers responding to the request to design for a small to medium size sinkhole by asking: Is it really that bad? The NHBRC-stimulated interaction

has and will hopefully continue to allow professionals to set aside misunderstandings through dialogue and arrive at better solutions which in turn benefit the home building industry.

Much discussion among dolomite stability investigators has centred on the issue of D2 and D3 designation. A long-standing struggle was the fact that the Home Building Manual indicated that D3 constituted a foundation in/on an enhanced earth mattress. This brought about confusion for very shallow dolomite sites where the mattress solution is not ideal (yet a better solution than the D2 design is needed). The geologist must ensure that the design will not fall short of the anticipated risk! This problem has to a certain degree been bridged by the modification presented in the 2001 paper by Buttrick *et al*, which alludes to the reinforced concrete grid spanning from pinnacle to pinnacle (proposed by Wagener) and other solutions. As it was/is beyond the scope of the paper, the issue of foundation solutions for D3 was not discussed. It would, however, be of great benefit if the authors could elaborate on this topic.

The authors:

INTRODUCTION

The paper focused on the deductive process that needs to be followed in order to arrive at the four Dolomitic Area Designations (see table 7 of the paper) that describe the necessary precautionary measures required to prevent the concentrated ingress of water into the ground on sites underlain by dolomites. In terms of this classification system, no precautionary measures are required in areas designated as being D1 and no houses may be constructed in areas designated as being D4. Areas designated as being D2 and D3 require such precautionary measures. However, areas designated as being D3 require precautionary measures in addition to those pertaining to the concentrated ingress of water into the ground.

Nicole Trollip's request for discussion on foundation solutions for D3 sites is very pertinent, as housing consumers and the NHBRC can be exposed to unacceptable risks should the 'precautionary measures, in addition to those pertaining to the concentrated ingress of water into the ground' required in sites designated as

being D3, not be correctly executed, or be misinterpreted. Even more so, the designer/competent person may be found negligent should a catastrophic event lead to an inquest and the practice followed by the professional be found to be deficient.

As the discussion centres on housing, the authors have confined their discussion to appropriate solutions for housing developments. For simplicity, the authors have confined the discussion to single-storey houses.

UNDERSTANDING THE PROBLEM

Sinkholes can occur at any point under or adjacent to the footprint of a structure. Apron slabs, which are commonly used to mitigate the effects of differential heave on structures and to move collapse settlements away from the footprint of the structure, have little effect on the location of a sinkhole. Accordingly, sinkholes having an Inherent Risk Characterisation (ie the chance for a certain size sinkhole or doline to occur within the postulated scenario of land use and dewatering or

non-dewatering) of 'high' as described in terms of table 6 of the paper can be expected to occur anywhere within the footprint of the structure. It must, however, be stressed that high-stand densities in areas of Medium Inherent Risk (Class 4) may change the Development Risk (ie likelihood and extent of loss of life, loss or damage to property or financial loss) from 'acceptable' to 'unacceptable', if mitigating measures are not implemented. These measures include special water precautionary measures and/or founding measures.

In order to maintain an Acceptable Development Risk, houses must either be designed to safely withstand the effects of sinkholes having an inherent risk characterisation of 'high' occurring anywhere under the footprint of the structure as indicated in figure 1 or measures need to be taken to reduce the risk of such sinkholes from occurring.

Dolines, on the other hand, occur where the premature termination of sinkhole formation occurs, or where the overburden material consolidates due to dewatering. Dolines that are due to the premature termination of sinkhole formation may be dealt with in the same man-

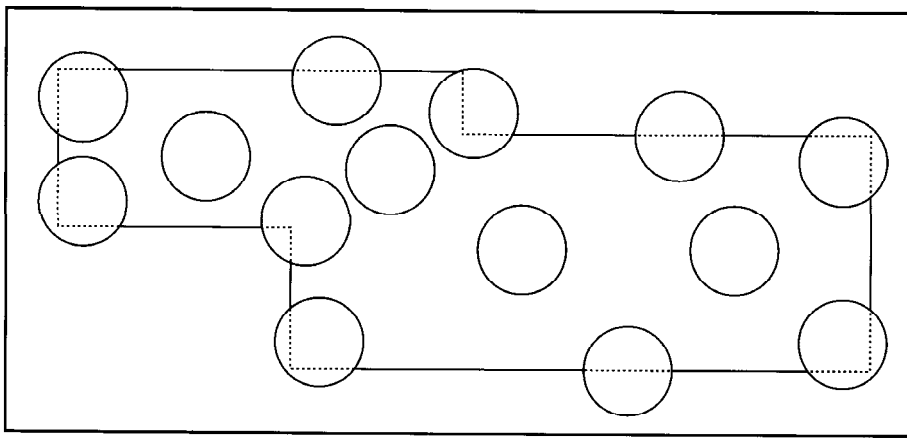


Figure 1 Critical locations of sinkholes under the footprint of a house

Table 1 Performance requirements for houses

Description	User needs	Performance description
Structural safety	The risk of collapse or other kind of severe damage resulting from structural failure, which may affect the life safety of the dwelling occupants or people in the vicinity of the building, shall not exceed a level acceptable to the user	The capacity of the whole house and its parts, with an appropriate degree of reliability, to maintain their strength and stability under all actions likely to occur during its design life
Structural serviceability	The structural behaviour of a house, under normal use and condition, that may affect: <ul style="list-style-type: none"> the efficiency and appearance of the house and its components the functioning of the occupants and the equipments in the house, and the comfort of the occupants is to be kept at a level acceptable to the users 	The performance description is the ability of the whole house and its parts, with an appropriate degree of reliability, to perform adequately for normal use under all expected actions. It can be described in terms of: <ul style="list-style-type: none"> local damage (including cracking) (which may affect the efficiency and appearance of the house and its components) unacceptable deformation (which may affect the efficient use or appearance of the house or the functioning of the people and equipment) excessive vibration (which may cause discomfort to people or affect the functioning of the people and equipment)

ner as sinkholes. Accordingly, for the purpose of this discussion, only dolines resulting from the consolidation of the overburden will be discussed.

Dolomite risk management may require that areas of shallow groundwater levels are described as D3, although such areas may in their present state be low-risk areas. If the groundwater level is inadvertently lowered, doline formation may be generated if the original water level is located above bedrock in soil materials with a low dry density, high void ratio and high Compression Index.

Sites with dolines of this nature will only be encountered in Class 5 sites, ie where the water table is above the dolomite bedrock in soil material with low dry density, high void ratio and high compression index. In such circumstances, houses situated at the perimeter of the doline will be subject to differential settlements.

PERFORMANCE REQUIREMENTS FOR HOUSES

The draft ISO standard for Houses – Description of Performance (ISO 15928) establishes user needs and performance descriptions with respect to structural safety and structural serviceability in houses (see table 1). As indicated in table 1, performance levels need to reflect what is acceptable to the user.

The Joint Structural Division's Code of Practice for Assessment of the Performance of Housing Units in South Africa (2000) identifies a number of structural design considerations. These may be stated as follows:

1 In areas where a sinkhole can occur, its size must be such that it will not completely envelop a house or result in the toppling or sliding failure of a house into such a hole.

2 There must be sufficient time for occupants to escape from the house after the occurrence of a sinkhole.

3 Damage to the house after the occurrence of a sinkhole must be within acceptable limits.

Considerations 1 and 2 relate to structural safety whereas consideration 3 relates to structural serviceability. Consideration 1 effectively precludes the development of detached houses where the risk of medium sinkholes (2–5 m), large sinkholes (diameter of between 5 to 15 m) and very large sinkholes (greater than 15 m) is 'high'.

It should be noted that a high development density in a Class 4 area may result in a D3 designation rather than the usual D2 designation in order to maintain an 'Acceptable' Development Risk.

The risk of collapse or other kind of severe damage resulting from structural failure due to the loss of foundation support arising from sinkhole formation or severe differential settlement attributable to doline formation can be readily assessed using structural engineering principles. This can be done by assuming a loss of support equivalent to the diameter of a nominated sinkhole (2,0 m in Class 5 sites and 5,0 m in Class 3 and 4 sites which are designated as being D3) occurring anywhere under the footprint of a house or the likely magnitude of the differential settlement to which a house may be subjected to at the extremity of a doline. Thus the abovementioned Joint Structural Division's design considerations relating to safety can be readily assessed.

The damage to the structure after the occurrence of a sinkhole must, however, also be considered. In South Africa, most houses are of masonry construction. Accordingly, only this form of construction will be considered in this discussion.

Watermeyer and Tromp (1992) introduced the concept of expected damage (approximation of the probable damage) in respect of masonry walls and concrete slab construction. The description of a range of categories of expected damage for masonry walls and concrete floors are presented in tables 2 and 3, respectively. The allowable deflection ratios used in the design of foundations to attain a category of expected damage no more severe than category 1 are tabulated in table 4 (Joint Structural Division 1995).

The Joint Structural Division's code of practice (1995) requires that damage resulting from movements within near surface soil horizons (ie swelling, shrinkage, collapse settlement and consolidation) should not be more severe than that associated with category 2. The code does, however, recommend that category 1 damage be designed for where houses are subject to movements associated with heaving clays. The National Home Builders Registration Council have adopted these recommendations and have framed their standards around these levels of expected damage. The Joint Structural Division's code of practice

Table 2 Categories of expected damage with respect to masonry walls (after Watermeyer & Tromp 1992)

Category and degree of expected damage	Description of damage in terms of ease of repair and typical effects
Minor damage – categories 0 to 2	
0 Negligible	Hairline cracks less than about 0,25 mm width are classed as negligible
1 Very slight	Fine internal cracks which can easily be treated during normal decoration. Cracks rarely visible in external masonry
2 Slight	Internal cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks not necessarily visible externally. Doors and windows may stick slightly
Significant damage – categories 3 to 5	
3 Moderate	Cracks can be repaired and possibly a small amount of masonry may have to be replaced. Articulation joints may have to be cut in some of the walls. Doors and windows sticking. Rigid service pipes may fracture. Weather-tightness often impaired. Up to 10 mm gap between ceiling cornices and walls
4 Severe	Extensive repair work which includes breaking out and replacing sections of walls, especially over doors and windows, cutting of articulation joints in walls and the construction of moisture trenches and apron slabs around the structure, or the jacking of foundations, depending on the type of soil movement. Window and door frames distorted, floor sloping noticeably, some loss of bearing in beams. Service pipes probably disrupted. Up to 20 mm gap between ceiling cornices and walls
5 Very severe	Major repair work required, involving partial rebuilding and the abovementioned repair techniques. Beams lose bearing, walls tilt badly and require shoring. Windows broken and distorted. Danger of instability

Table 3 Categories of expected damage with respect to concrete floors (after Watermeyer & Tromp 1992)

Category and degree of expected damage	Description of typical damage
Minor damage – categories 0 to 2	
0 Negligible	Hairline cracks, insignificant tilt of floor or change in level
1 Very slight	Fine but noticeable cracks. Floor reasonably level
2 Slight	Distinct cracks. Floor noticeably curved or changed in level
Significant damage – categories 3 to 5	
3 Moderate	Wide cracks. Obvious curvature or change in level – local deviation of slope from the horizontal may exceed 1:100
4 to 5 Severe to very severe	Gaps in floor. Disturbing curvature or change in level



Figure 2 Recent 'medium' sinkhole in a high-density residential development

(2000)), however, requires that damage in areas underlain by dolomites should not be more severe than that associated with category 4. This level of expected damage is consistent with the aforementioned safety requirement that there must be sufficient time for occupants to escape from the structure after the occurrence of a sinkhole.

Serviceability requirements are based on acceptable performance under normal day-to-day loadings (eg gravity loads, wind loads, seismic loads, temperature, etc), issues of appearance, protection of the interior of housing units from the elements, and, in some instances, human comfort. There is a point of diminishing return when it comes to the prediction of probable property damage. For a given cost, a certain level of probable property damage reduction is attained. It then becomes a problem of economics to weigh the present value of the investment costs against the cost of future property losses and the loss of the use of the property. Moreover, the problems of economics must be placed in a probabilistic framework, since the losses are associated with a natural hazard that has a probability of occurrence.

The following fundamental questions need to be answered before proceeding with any engineering solution:

- What level of expected damage must be designed for in respect of sinkholes and dolines?
- What are the implications and costs associated with the repairing of a sinkhole?

Figure 2 illustrates the extent of a medium sinkhole in a high-density residential development

ENGINEERING SOLUTIONS

Geotechnical solutions

Geotechnical solutions improve the material on the plan area of the development by

- the removal of unsuitable material and replacement with selected, compacted granular fill
- the removal of material and return of same with controlled compaction in layers, or
- in-situ compaction by methods such as dynamic consolidation

In this way, the highly variable material is improved to form a mattress of known strength and suitable thickness below the structure. This mattress of soil not only reduces differential settlements but improves the impermeability of the material overlying the sensitive, unstable dolomite and hence reduces the risk of sinkhole and doline formation occurring beneath the structure. It also forms a relatively competent roof over any small- and medium-sized cavities that may form below the structure.

Table 4 Allowable deflection ratios to limit expected damage to that of Category 1 (Joint Structural Division 1995)

Type of masonry	Allowable deflection ratio	
	Unreinforced	Lightly reinforced
Hogging movements		
Articulated masonry		
• plastered	1:800	1:600
• face	1:650	1:500
Full masonry		
• plastered	1:2000	1:1250
• face	1:1500	1:1000
Sagging movements		
Articulated masonry		
• plastered	1:500	1:500
• face	1:350	1:300
Full masonry		
• plastered	1:1000	1:500
• face	1:500	1:300

Table 5 Classification according to average thickness of overburden (Wagener 1981)

Class	Description
A	Pinnacle and boulder dolomite overlain by moderately thick overburden ($c < 3$ m)
B	Pinnacle and dolomite overlain by moderately thick overburden ($3 \text{ m} \leq c \leq 15$ m)
C	Pinnacle and boulder dolomite overlain by thick overburden ($c > 15$ m)

c = the average thickness of the overburden to tops of pinnacles and boulders

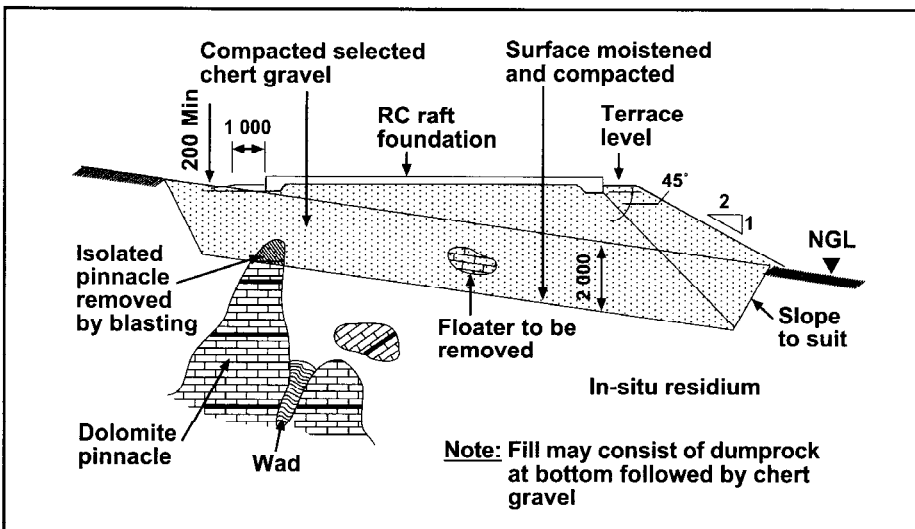


Figure 3 Mattress on a class B or C site (thick cover over pinnacles and boulders) (Wagener 2002)

The thickness of the mattress will depend on a number of factors, the most important being (Wagener 2002)

- the thickness and properties of the soil overlying pinnacles and boulders
- the properties of the in-situ soil below the mattress, and
- the sensitivity of the proposed structure to settlement

The mattress may be constructed using conventional equipment to excavate material and compact the fill or dynamic consolidation. The method of mattress construction is best determined after a number

of trenches (3 to 4 m deep) have been excavated and profiled to determine the thickness of soil cover over pinnacles and boulders as well as the nature of the material.

The stress distribution below a mattress approximates to a 45° load spread. This property is explored in the design of mattresses. (Wagener 1985, 2002). In class A sites (see table 5) the mattress tends to distribute the loads into the pinnacles by arching. In class B and C sites (see table 5), the mattress spreads the load to weaker underlying layers.

On class A sites (see table 5), where rockfill is available, the material is typically removed to a depth of about one

metre below tops of pinnacles and large boulders, and is backfilled with rockfill to about 200 mm above the pinnacles. Thereafter, the remainder of the terrace is constructed with selected chert gravel or other suitable granular material placed under controlled conditions (Wagener 1985, 2002). On class B and C sites, the thickness of the mattress is typically between 1,5 and 2,5 m in thickness. Slab-on-the-ground foundations, in accordance with the provisions of the Joint Structural Division's code of practice (1995), are most appropriate where mattresses are constructed as they are relatively shallow and distribute loads effectively. There is no point in providing a mattress and then excavating through it, to found the house.

It is difficult to construct mattresses on steeply sloping sites or for a house with the ground floor on different levels as the continuity of the mattress is compromised. In these instances consideration should be given to a suspended floor system resting on columns that are supported by stub columns or piles anchored into bedrock.

Structural solutions

Founding on pinnacles

Where abundant pinnacles occur in close proximity to the surface, they can be used as 'supports' for a reinforced concrete grid spanning from pinnacle to pinnacle. If support positions are required in between the pinnacles, these can sometimes be created using stub columns or piles anchored into bedrock.

Raft foundations

The following foundation types, designed in accordance with the provisions of the Joint Structural Division's Code of Practice for Foundations and Superstructures for Single Storey Residential Buildings of Masonry Construction, are suitable:

- stiffened raft foundations (grid of reinforced/ post-tensioned concrete beams cast integrally with the floor slab)
- stiffened strip footings (reinforced grouted cavity wall construction with interconnected floor slabs), or
- cellular raft foundations (two horizontal reinforced concrete slabs interconnected by a series of webs)

The raft should be designed to span over a 'soft spot' (loss of support) of a given diameter (see Holland 1981 and Joint Structural Division 1995).

Floor slabs should be reinforced and connected to or supported by all edge and stiffening beams. Failure to do so may result in slabs in small rooms toppling or sliding into sinkholes. Alternatively, slabs which are only supported on two sides at a corner, may collapse should a sink hole occur at a corner.

Table 6 Site class designations (Watermeyer & Tromp 1992)

Typical founding material	Character of founding material	Expected range of total soil movements (mm)	Assumed differential movement (% of total)	Site class
Rock (excluding mud rocks which may exhibit swelling to some depth)	Stable	Negligible	–	R
Fine-grained soils with moderate to very high plasticity (clays, silty clays, clayey silts and sandy clays)	Expansive soils	< 7,5 7,5–15 15–30 > 30	50% 50% 50% 50%	H H1 H2 H3
Silty sands, sands, sandy and gravelly soils	Compressible and potentially collapsible soils	< 5 5–10 > 10	75% 75% 75%	C C1 C2
Fine-grained soils (clayey silts and clayey sands of low plasticity), sands, sandy and gravelly soils	Compressible soils	< 10 10–20 > 20	50% 50% 50%	S S1 S2
Contaminated soils, controlled fill, dolomitic areas, landslip, landfill, marshy areas, mine waste fill, mining subsidence, reclaimed areas, uncontrolled fill, very soft silts/silty clays	Variable	Variable		P

Piled foundations

Piled foundations may also provide a viable solution under certain circumstances. Extreme care must, however, be taken in order to ensure that the piles are socketed into pinnacles or bedrock as opposed to floaters.

All pile foundations should be proof-drilled for a minimum of 6 m of solid rock.

RECOMMENDATIONS FOR HOUSING IN D3 SITES

It must be remembered that, in accordance with the addendum to the Joint Structural Division's code of practice (1998), sites need to be classified in terms of both the dolomitic area designations and site class, viz Class P (Dolomites – D3/x), where x is the symbol describing the founding characteristics. The recommendations given below are generally suitable for site class designations H, C, S, C1, S1 and C2 and, in some instances, site class S2 (see table 6).

Dolines

Stiffened strip footings or stiffened/cellular rafts with articulation joints or solid lightly reinforced masonry in accordance with the provisions of the Joint Structural Division's code of practice (1995) should be provided. (These solutions will be similar in nature to those for sites designated as being class S2. It will, however, not be possible to predict the axis through the structure about which the differential movements will take place.)

Split construction in accordance with the provisions of the Joint Structural Division's code of practice (1995) may also be provided. (This solution will be the same as that for sites designated as being class H2.)

The category of expected damage should be no more severe than category 2.

Sinkholes

Stiffened strip footings or stiffened or cellular rafts or reinforced concrete grids spanning from pinnacle to pinnacle with articulation joints or solid lightly reinforced masonry, in accordance with the provisions of the Joint Structural Division's code of practice (1995), should be provided for sites with an Inherent Risk Class of 5 (see table 6 of the paper). The design criteria should be that the foundations withstand a loss of support over an area having a diameter of 2,0 m, occurring anywhere under the footprint of the house, and restrict damage in such an event to that associated with category 2 expected damage. (These solutions will be similar or slightly more substantial than sites designated as being class C2, as the code's design criteria for such sites is that the minimum dimension of soft spots occurring beneath the house, in the most adverse location, should not be less than 1,5 m.)

An alternative solution, on sites with an Inherent Risk Class of 5, is the installation of a soil mattress as described by Wagener (1985, 2002) and to provide a foundation system placed on top of the mattress, capable of withstanding a loss of support over an area, occurring anywhere under the footprint of the house, having a diameter in metres of

- 2,0 with the damage associated, with such an event not being more severe than category 4 expected damage, and
- 2,0 minus twice the thickness of the mattress below the base of the perimeter foundations, with the damage associated with such an event not being more severe than category 2 expected damage

A slab-on-the-ground foundation, in accordance with the provisions of the Joint Structural Division's code of practice, constructed on top of the mattress with three additional Y12 bars being placed in the top of the perimeter edge beam, satisfies the above criteria if the overall thickness of the mattress is not less than 1,3 m.

In low-cost housing developments, where the cost of repairing a sinkhole is large in proportion to the value of the house, it is recommended that the abovementioned mattress and slab-on-the-ground-foundation solution be adopted.

Where sites having an Inherent Risk Class of 3 or 4 are classified as being D3 because of subsurface conditions or stand densities, it is recommended that soil mattresses as described by Wagener (1985, 2002) be installed to mitigate the effects of the subsurface conditions or stand densities. In such instances, it is recommended that the foundation system placed on top of the mattress be capable of withstanding a loss of support over an area, occurring anywhere under the footprint of the house, having a diameter in metres of

- 3,0, with the damage associated with such an event not being more severe than category 4 expected damage, and
- 5 minus twice the thickness of the mattress below the base of the foundations, with the damage associated with such an event not being more severe than category 2 expected damage

Although it is possible to design rafts to withstand the effects of 5,0 m 'soft spots' (see Holland 1981) by providing only a structural solution, it is not considered to be an appropriate solution. The cost and problems associated with the making good of a sinkhole, should it occur, far exceed any potential savings that would be made by opting for a structural solution over a geotechnical solution.

The authors do not recommend the construction of relatively small, detached, low-cost houses on sites having an Inherent Risk Class of 3 or 4 that are classified as being D3. In theory such developments can take place on sites having an Inherent Risk Class of 5. It must, however, be borne in mind that the cost of making good a 2 m diameter sinkhole on these sites is disproportionate to the value of these houses. Accordingly, it is recommended that relatively small, detached, low-cost houses, which are underlain by dolomites, should only be developed on Class 3 and 4 that are designated as being D2 sites.

In conclusion, the authors would like to stress that although there are geotechnical and structural solutions to reduce the risk of sinkhole formation in sites having an Inherent Risk Class of 3 or 4 that are classified as being D3, planners and engineers should realise that develop-

ment density on dolomite must be kept low. The costs and benefits of high-density developments on such land must be carefully considered.

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