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In Collaboration With

Association of Consulting Engineers Singapore · GeoSS · The Institution of Engineers Singapore

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Dear Sir/Madam

JOINT BCA/IES/ACES/GEOSS CIRCULAR 2025

GUIDELINES FOR THE DESIGN AND CONSTRUCTION OF BORED PILES IN LIMESTONE AREAS

OBJECTIVE

This is a joint BCA/IES/ACES/GEOSS circular to the industry on the 'Guidelines for the design and construction of bored piles in limestone areas'. This circular establishes a risk-based framework that standardises and consolidates existing good practices in the design and construction for bored piles in limestone areas characterised by cavities or slump zones. Drawing upon collective industry expertise, it harmonises existing practices to ensure project stakeholders can deliver safe and reliable foundation systems, and reduce unforeseen delays while ensuring consistency across projects. This circular also applies to barrette piles, which are another type of deep pile foundation.

BACKGROUND

2. The geological landscape in western Singapore includes natural limestone formations that feature cavities and slump zones. These naturally occurring limestone cavities typically exist at considerable depths from the ground surface, with a stable rock cover above them. There are no documented instances of these limestone cavities manifesting as surface sinkholes in Singapore thus far. Nonetheless, piles penetrating deep into the ground may encounter limestone cavities or slump zones during installation, posing construction challenges, and affecting their load carrying capacity. If limestone cavities and slump zones are not detected during the site investigation, it may impact project timelines and costs during the pile installation phase. Furthermore, inadequate resource allocation during tender stages may compromise pile installation quality, raising safety concerns on the adequacy of the piled foundation.

3. BCA has developed the guidelines through extensive consultation with industry stakeholders. This collaborative effort included engagement with piling contractors, site investigation companies, geophysical survey companies, grouting specialists, consultants, academia, professional institutions and government agencies. Numerous dialogue and feedback sessions were held to co-create the guidelines and incorporate the valuable insights gained.

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4. For developments in areas with challenging ground conditions, particularly those with potential limestone cavities or slump zones, thorough site investigation must be conducted at the early project stages. It is incumbent upon Developers, Builders, and Qualified Persons (QPs) to ensure these assessments are properly executed and their findings incorporated into the design and construction methodology for foundation piles. This proactive approach will help safeguard against construction delays and ensure that the safety of pile foundation is not compromised.

5. This circular contains 3 annexes:

Annex A	Guidelines for the design and construction of bored piles in limestone areas
Annex B	Good practices for executing geophysical surveys
Annex C	Good practices for limestone cavity logging in boreholes

6. Annex A shall be complied with when making structural plan submissions involving foundation bored piles and barrette piles to the Commissioner of Building Control for approval. Annexes B and C outline recommended good practices to achieve the intended safety and quality outcomes. This circular shall supplement the BCA/IES/ACES/GEOSS circular (APPBCA-2016-08) for projects in limestone areas with a risk of cavities or slump zones. This circular applies to all projects except those that submitted their Planning Permission application to URA before **1 Mar 2026** and subsequently received Provisional Permission (PP) or Design Gateway (DG) clearance. For projects that do not require URA's Planning Permission, this circular applies if their first structural submission is on or after **1 Mar 2026**.

7. QPs are reminded to exercise their professional engineering judgment in design and supervision and undertake appropriate evaluation and implement suitable measures to meet the Objectives and Performance Requirements specified in the Fifth Schedule of the Building Control Regulations 2003, along with relevant standards and codes of practice.

CLARIFICATIONS

8. We would appreciate if you could disseminate the contents of this circular to your members. Please contact us at Tel: 1800-3425222 or through the online feedback form (https://www.bca.gov.sg/feedbackform/) should you require any clarifications. Thank you.

Yours faithfully,

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Project professionals shall conduct their own independent assessment and verification to determine the applicability and sufficiency of the information provided for their specific project requirements.

This guide supplements and does not supersede the statutory requirements under the Building Control Act and Regulations. All stakeholders, including developers, Qualified Persons, site supervisors, and builders, remain bound by their statutory obligations to ensure that building works are designed and carried out in full compliance with the Building Control Act and Regulations, exercising due diligence throughout the project lifecycle.

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ANNEX A: GUIDELINES FOR THE DESIGN AND CONSTRUCTION OF BORED PILES IN LIMESTONE AREAS

1. Scope of guidelines

1.1 The growing development of western Singapore presents geotechnical challenges in foundation piling works due to presence of limestone containing cavities or slump zones. Project parties, who lack adequate knowledge of such ground conditions and fail to implement appropriate measures, may suffer substantial delays and additional cost during construction. The complications typically arise from the necessity to conduct additional site investigations (SI) followed by cavity treatments, which disrupt the pile installation activities on site.

1.2 The guidelines provide a framework adopting a risk-based approach, to stipulate the requirements at each project stage (i.e. SI, pile design, pre-piling cavity treatment, pile installation, pile testing) to minimise the risks associated with pile design and construction in such ground conditions. They are developed based on the collective industry knowledge and experiences of bored pile design and construction in such geological formations.

2. Occurrence of limestone in Singapore

2.1 Limestone is susceptible to dissolution, forming karstic features such as cavities and slump zones. Cavities are voids that occur within limestone, and slump zones are zones of soft, weak material that overly the limestone bedrock and may infill cavities. These features pose safety risks and challenges to the design and construction of piled foundations. Limestone can be found in 4 geological formations (Pandan Formation, Tuas Formation, Pulau Ayer Chawan Formation and Boon Lay Formation) and 2 geological members (Nanyang Member, Clementi Member) of the Jurong Group. The distribution of these geological units is shown in **Figure A1**, and their respective limestone content is illustrated in **Table A1**.

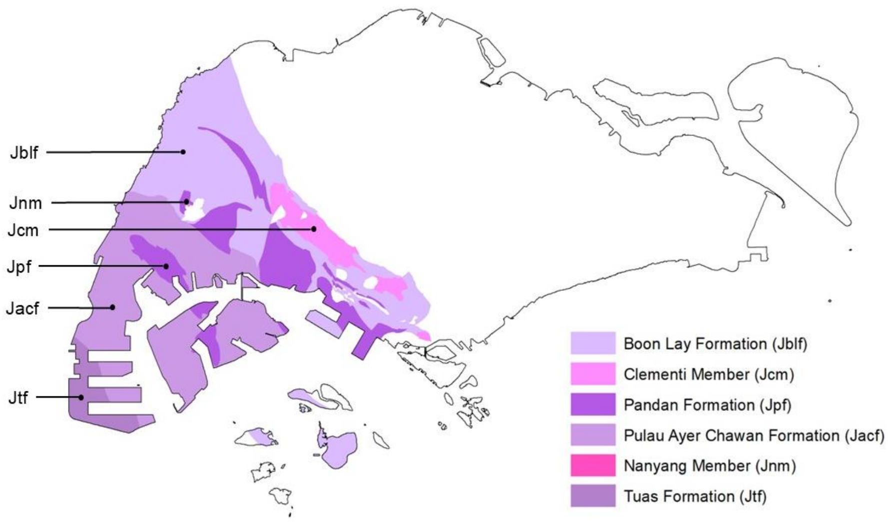


Figure A1 – Geological units containing limestone in western Singapore (modified from Leslie et al., 2021)

Table A1 ─ Archetypal limestone character of geological units (Gillespie et al., 2021)

Geological Formation	Limestone Character
Boon Lay Formation	1% carbonate rock; occasional 1-3 m thick limestone beds.
Clementi Member	1% carbonate rock; thin beds of reddened carbonate rock may develop locally.
Pandan Formation	72% carbonate rock; 5-50 m thick limestone beds.
Pulau Ayer Chawan Formation	11% conglomerate which may contain limestone clasts.
Nanyang Member	Unspecified percentage of carbonate rock; may contain entrained limestone clasts.
Tuas Formation	23% carbonate rock; 1-20 m thick limestone beds.

2.2 The geology in western Singapore is complex, affected by numerous fold and thrust zones. The bedrock geological map (BCA, 2021) shows the geological formations near the ground surface. At greater depths, other geological formations may be encountered. For example, geological formations containing a higher limestone content and greater risk of encountering cavities, such as the Pandan Formation, may be found underlying the younger Boon Lay Formation or Clementi Member, as illustrated in **Figure A2**. QPs will need to exercise vigilance when assessing the geological formation(s) of a project with pile foundation.

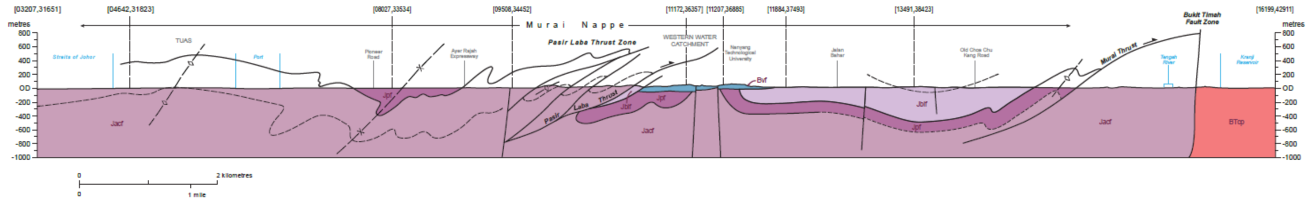


Figure A2 ─ Schematic cross section (1: 50,000 scale) showing the general relationships of bedrock in western Singapore (Gillespie et al., 2021)

2.3 Cavities can be found in both rock and soils. **Figure A3** illustrates limestone cavities encountered in boreholes from some past projects (non-exhaustive). This figure should only be used as a first cut, and project parties should exercise due diligence to ascertain the actual site conditions. There are also reports of cavities found within the soils of the Pandan Formation and Boon Lay Formation, possibly due to the dissolution of limestone boulders or fragments within the soil.

2.4 In Singapore's context, limestone cavities can contain air, water, cavity-fill deposits (soils, rock fragments), or a combination of these materials. Slump zones appear as a 'slime' or 'slurry' and are usually identified by very low standard penetration test 'N' values or low cone resistance.

2.5 According to NA to SS EN 1997-2:2010 (2020), a preliminary desk study is an essential prerequisite for all site investigations. This initial assessment enables stakeholders to evaluate the likelihood of encountering limestone formations and associated cavities at the preliminary project stage.

2.6 The desk study shall encompass a comprehensive review of available geological and historical data, including but not limited to the following. This systematic evaluation provides a preliminary geological overview of the site, and aids the identification of potential limestone formations, cavities and slump zones, which may impact the project.

(a) Previous site investigation and geophysical survey records from adjacent sites
(b) Geological memoirs and documents
(c) Historical maps and aerial photographs
(d) Historical land use records and development history
(e) Remotely sensed data and imagery
(f) Other pertinent geological and geotechnical documentation

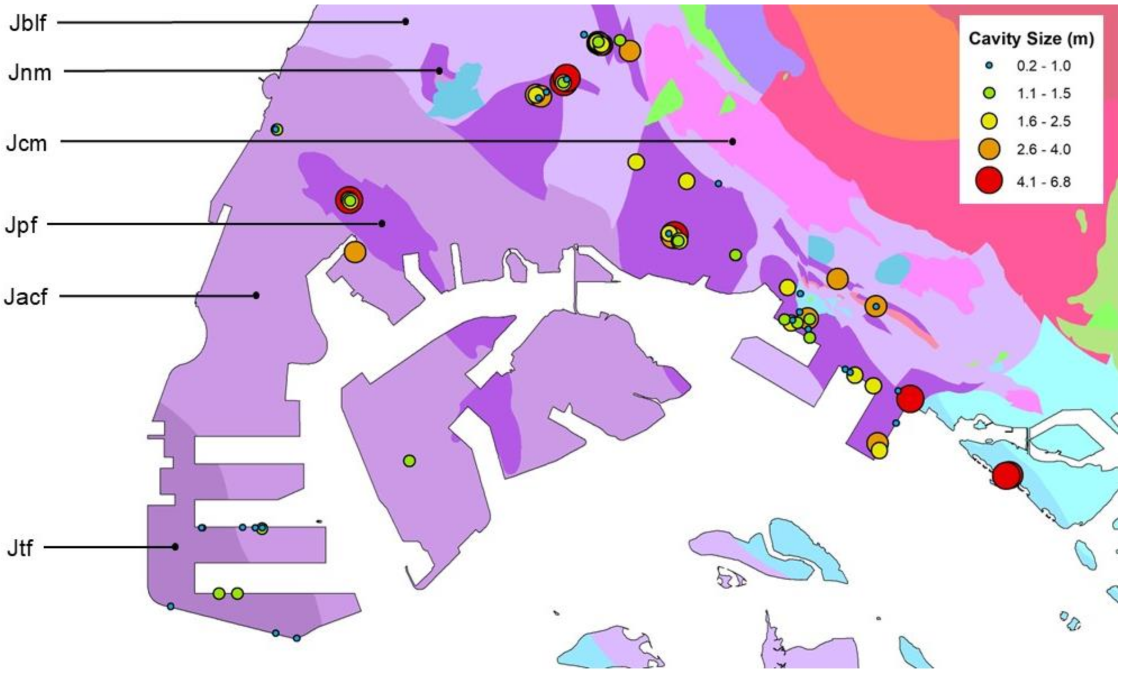


Figure A3 – Location of boreholes from past projects which encountered limestone cavities (non-exhaustive) dated Mar 2025

3. Risk categorisation of projects in limestone areas

3.1 A risk-based approach is proposed to categorise the risk level of a project with bored pile foundation, with consideration of the geological formations and the building types. Ground with higher content of carbonate rock, and hence higher possibility of encountering cavities, is assigned a higher geological risk. Building risk is assessed in consideration of the building height as well as the critical nature of the structures supported by the piles.

3.2 The risk level is classified into the following categories: 'Very High', 'High', 'Medium', and 'Low'. The risk category of the project will then be used to determine the requirements for the boreholes, probe holes, geophysical survey, pile design, pile construction and pile testing. **Table A2** shows the matrix for categorising the risk of projects.

4. Phasing of works

4.1 It is recommended for the works to be carried out in phases, as shown in **Figure A4**. This phasing of works will enable the piling works to be carried out with minimal disruptions.

4.2 For working piles without probe holes in the original plan, if a cavity is encountered during pile boring (Phase 4), the pile should be probed, with the cavity treated, followed by installing the pile to the depth as per the revised design by the QP.

Table A2 – Matrix for risk categorisation[1] of projects

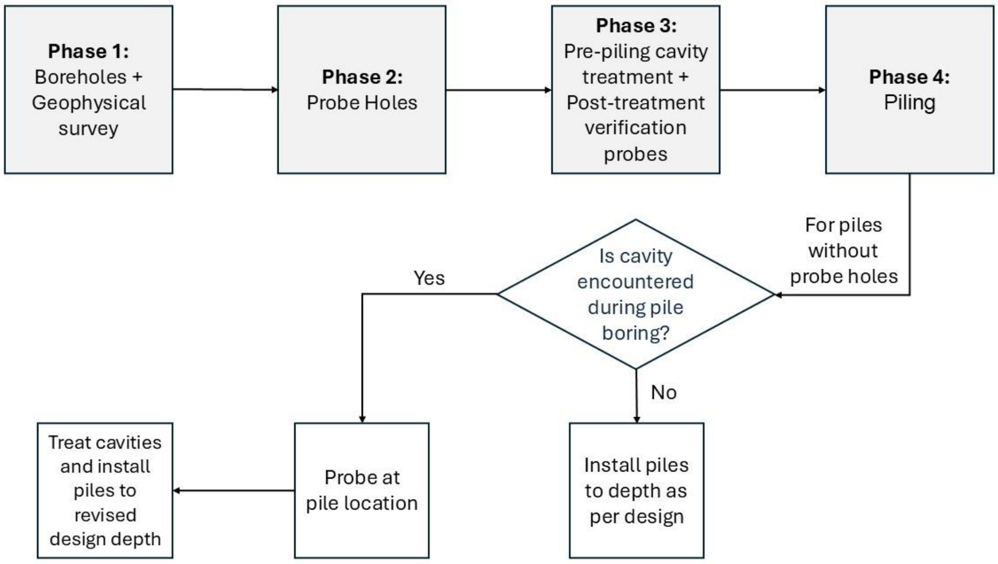
Geological Formation[2] \ Building Type	Building of ≥ 30 storeys; Bridges, viaducts, piers	Building of 10 to 29 storeys	Major building works of < 10 storeys
Geological Group 1 Pandan Formation, Tuas Formation	Very High	High	Medium
Geological Group 2 Boon Lay Formation, Pulau Ayer Chawan Formation, Nanyang Member, Clementi Member	High	Medium	Low

Footnotes for Table A2

[1] If the site investigation does not reveal any limestone, cavities, or slump zones, the pile design works may proceed in accordance with the BCA/IES/ACES/GEOSS circular (APPBCA-2016-08). However, for 'Very High' and 'High' risk projects, the QP(S) and Site Supervisor must conduct acid tests on rock samples at appropriate depth intervals for every working pile during pile construction to verify the continued absence of limestone. Should any limestone, cavities or slump zones be subsequently discovered through acid testing, boreholes, probe holes, or pile boring operations, the requirements specified in this circular shall apply.

[2] When multiple geological formations are identified within a single building footprint, the higher risk category should generally be adopted. Nevertheless, the QP may, through careful assessment and due diligence, propose to subdivide the building footprint into sub-zones, each assigned with its appropriate risk category.

Figure A4 – Recommended phasing of works



5. Site investigation

5.1 The BCA/IES/ACES/GEOSS circular (APPBCA-2016-08) stipulates the minimum number of boreholes for foundations of: (1) Buildings of 10-storeys or more; (2) Buildings of 5 to 9 storeys with footprint larger than 100 m^2. The circular (APPBCA-2016-08) specified that a more comprehensive site investigation is essential for complex geological conditions such as limestone, bouldery ground and underground cavities.

5.2 This circular provides guidelines covering the borehole and probe hole requirements for limestone areas. **Table A3** lists the site investigation requirements corresponding to each project's risk category.

5.3 For all risk categories, the minimum depth of the boreholes and probe holes is required to be not less than the influence zone below the pile toe, which is defined as below:

(a) For single piles: the greater of (i) 5 m beyond the intended pile toe termination; (ii) 3 times the pile diameter beyond the intended pile toe termination.

(b) For pile groups: the greater of (i) 10 m beyond the intended pile toe termination; (ii) 6 times the pile diameter beyond the intended pile toe termination.

Probe holes shall only terminate after achieving a continuous rock without cavities or slump zones for the above specified minimum depth.

The influence zone beneath a pile or pile group refers to the soil or rock region where stress changes resulting from applied loads are substantial. With reference to Clauses 5.3(b), 6.4, and 7.2, QPs for any project seeking to propose an alternative depth for the influence zone must provide appropriate justifications for their proposal.

5.4 When boreholes encounter any slump zones or cavity-fill deposits, standard penetration tests should be conducted in closer intervals than standard practice.

5.5 The boreholes are advised to be supervised by experienced personnel, e.g. site supervisors with a track record of working in limestone areas.

5.6 The boreholes should be backfilled with a suitable material upon completion by the SI company. The probe holes should be grouted with a suitable material of a similar concrete strength to that of the bored or barrette pile upon completion by the grouting specialist. This is particularly important for piles which encounter limestone cavities and the end bearing resistance is considered in design.

5.7 If the QP is satisfied with the reliability of the geophysical survey results in providing cavity information at the pile positions, the QP may propose to reduce the number of probe holes.

5.8 For ‘Very High’ and ‘High’ risk projects, the Developer is required to make provisions for the advance works before the piling contract is awarded. The advance work provisions should include boreholes, probe holes, geophysical surveys (if required or deemed necessary), to comprehensively map and characterise any limestone cavities within the site.

Table A3 – Borehole and probe hole requirements[3] by risk category

Requirements / Risk Category	Boreholes (Phase 1)	Probe Holes[4] (Phase 2) Min. percentage of working piles that require probe holes		
		Scenario A[5]	**Scenario B[6]**	**Scenario C[7]**
Very High	Min. 1 BH per 100 m^2 (buildings), subject to min. 2 per block; Min. 1 BH per pier (critical infrastructure)	80%	20%	Not Applicable
High	Min. 1 BH per 150 m^2, subject to min. 2 per block	60%	15%	
Medium	Min. 1 BH per 200 m^2, subject to min. 2 per block	40%	10%	
Low	Min. 1 BH per 300 m^2	20%	5%	
		For all scenarios[8] - If cavities are encountered by any of these probe holes, every pile adjacent[9] to this cavity should have an additional probe hole.		

Footnotes for Table A3

[3] The borehole and probe hole requirements are only applicable to zones within the project site with a presence of limestone.

[4] Probe holes refer to small-diameter holes (typically ~100 mm hole diameter) aimed at quick assessments of cavities or slump zones at working pile positions.

[5] Scenario A refers to 'if any borehole encounters limestone with cavities or slump zones'.

[6] Scenario B refers to 'if any borehole encounters limestone but no cavities or slump zones'.

[7] Scenario C refers to 'if any borehole does not encounter any limestone, cavities or slump zones'.

[8] For all scenarios, if the adjacent probe holes show results that differ from the initial scenario-based classification, the QP should propose a corresponding change of scenarios, and the respective probe hole requirements will apply.

[9] An 'adjacent' pile refers to any pile that falls within 3 times the pile diameter of the cavity pile, measured from the pile centre.

6. Geophysical survey

6.1 Geophysical surveys measure signals from contrasting physical properties of subsurface media (rocks, soils, cavities, fractures, etc.). When complemented with invasive SI methods (e.g. boreholes and probe holes), geophysical surveys provide valuable information for a comprehensive assessment of subsurface conditions.

6.2 The wide-area geophysical survey should be performed upfront during the SI stage to highlight potential zones with a high probability of encountering limestone cavities or slump zones. This allows the locations of the boreholes and probe holes to be targeted and optimised. The geophysical survey is meant to be a complement, not a replacement, of invasive SI. The design of the geophysical survey should be commensurate with the expected extent of the limestone cavities or slump zones (e.g. in terms of the layout of the survey lines, survey depth, resolution, etc.).

6.3 Table A4 shows the requirements of geophysical survey for various risk categories.

Table A4 – Requirements of geophysical survey

Risk Category	Geophysical Survey
Very High and High	Required if ≥ 25% boreholes encountered limestone with cavities or slump zones. If 100% of the working piles have probe holes, geophysical survey is not required.
Medium and Low	Recommended if boreholes encountered limestone with cavities or slump zones.

6.4 The minimum depth of the geophysical survey is recommended to cover the influence zone defined in Clause 5.3.

6.5 The good practices for executing geophysical surveys are detailed in **ANNEX B.** The QP shall determine the most suitable geophysical method(s) based on the site conditions and survey objectives (e.g. depth and resolution). Guidance on selecting surface geophysical methods can be found in ASTM D6429-23 and BS 5930:2015+A1:2020.

6.6 Geophysical surveys are often adopted to mitigate the risk of unforeseen ground conditions and enhance overall safety. Compared to invasive SI, the competitive advantages of geophysical survey include:

(a) More comprehensive coverage
   (i) Greater spatial and depth coverage.
   (ii) Continuous profiling (geophysics) vs. discrete sampling (invasive SI).

(b) Enhanced detection capabilities
   (i) Multiple methods can be adopted for cross-validation.
   (ii) Acquired data can be interpreted for various applications (limestone cavities, engineering rockhead depth, fracture zones, etc.).

(c) Time and cost-effective site investigation
   (i) Targeted investigation of anomalous zones.
   (ii) Optimise locations of invasive SI.
   (iii) Savings in quantities of invasive SI.
   (iv) Usually less costly than invasive SI.

6.7 Geophysical surveys also possess certain limitations:
(a) Technical constraints
   (i) Choosing the appropriate geophysical method.
   (ii) Site conditions (noise, obstructions, geology) may affect data quality.
   (iii) Resolution may degrade with depth.
   (iv) Non-unique geological solutions may require calibration and validation.
   (v) Cannot fully replace invasive SI.

6.8 To overcome the above limitations, it is recommended that professional guidance should be sought for geophysical survey design and interpretation. Project parties are required to share available invasive SI data (e.g. boreholes, probe holes) with the geophysical contractor to calibrate, refine and validate the geophysics results through an iterative process.

7. Pile design requirements

7.1 The requirements in this section are applicable to the zone encountering limestone with cavities. The presence of cavities around a pile will reduce its geotechnical capacity. If a cavity is below the pile toe, the pile end bearing resistance will be affected. The probable reduction of the skin friction and end bearing resistance should be taken into consideration in the design of bored and barrette piles by the QP.

7.2 End bearing resistance (Q_b): **Table A5** shows the pile design requirements by risk category. Refer to **Figure A5** for the case illustration, and to Clause 5.3 for the definition of influence zone.

Table A5 – Design requirements by risk category

Risk Category	**Design Requirements**
Very High and High Medium	Case A (Preferred): If end bearing resistance is considered in design, there shall be no cavities within the influence zone. Case B If cavities are within the influence zone but are separated by competent rock of at least 3 m or 1.5 times the pile diameter (whichever is greater) below the pile toe, end bearing resistance shall be ignored in design. The cavities shall be fully grouted. Case C (Not allowed) No cavities are allowed within the greater of 3 m or 1.5 times the pile diameter (whichever is greater) below the pile toe. The pile shall not terminate within this zone.
Low	If cavities are found within the influence zone, and the QP decides to terminate the pile there, the end bearing resistance of the pile shall be ignored in design. The cavities shall be fully grouted. Such piles shall be chosen for the working load test.

7.3 Skin friction at cavity location (F_{s2}): The skin friction resistance at the cavity location should be ignored, regardless of whether the cavity is treated with grouting or cased with permanent steel casing.

7.4 Skin friction above the cavity (F_{s1}): As the cavity may not be fully filled, the cavity roof may collapse into the partially filled hole in the long term. The skin friction of the pile above the cavity may be reduced if the cavity size is large. Hence, the QP should assess and determine the need to reduce the shaft friction above the cavity in pile design. This can be done by increasing the partial resistance factor R4 or ignoring part of the shaft friction above the cavity.

7.5 Skin friction for permanent steel casing: Contribution of skin friction for the entire casing length should be ignored.

7.6 Additional Verification Check: Designers must ensure compliance with SS EN 1997-1 design requirements. For bored and barrette piles classified under 'Medium' to 'Very High' risk categories, additional verification check is required as follows:

(a) The characteristic shaft resistance must be at least 1.5 times the pile working load. This requirement may be waived only if pile base resistance enhancement methods are implemented on site with appropriate testing verification.

(b) Where no cavities are encountered during construction, the characteristic shaft resistance of bored piles can remain as 1.3 times the pile working load, in accordance with Clause 5.2 of the BCA/IES/ACES/GEOSS circular (APPBCA-2016-08).

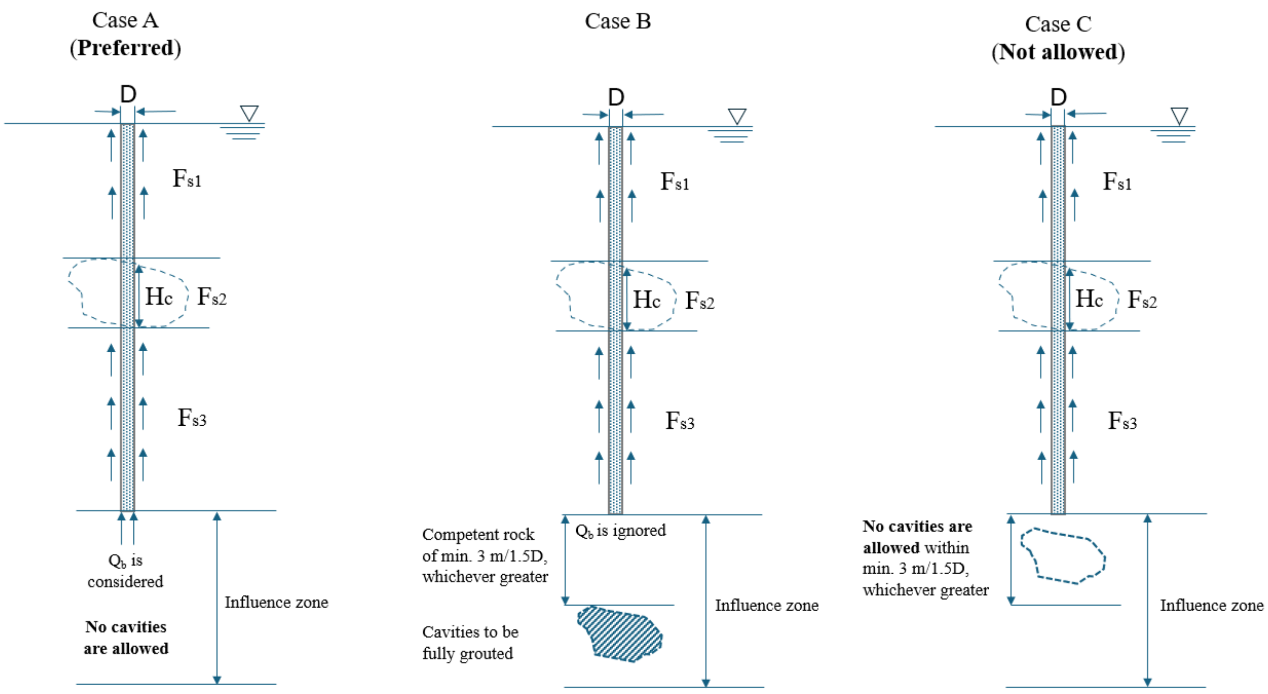


Figure A5 – Design consideration for end bearing resistance and pile toe termination criteria

8. Pre-piling treatment of cavities at pile location

8.1 Any cavities detected during SI or probing at pile locations are to be pre-treated before the commencement of actual pile installation. The main purpose of the pre-piling treatment is to facilitate pile concreting at the cavity zones to enable the proper formation of bored or barrette piles.

8.2 Multiple cavities: For multiple cavities at the same pile location, the sequence of the grouting should be from the deepest cavity to the shallowest one.

8.3 Verification Probes: Verification probes are post-grouting test holes drilled into the treated ground to assess the effectiveness and completeness of the grouting works. It is a quality assurance tool for confirming whether the grout has adequately filled the voids, fissures or cavities within the limestone formation. Grouting specialists are required to ensure such verification probes are appropriately done by checking whether there are abrupt changes in the penetration rate or water loss during the drilling process. Before bored or barrette pile installation, there should be adequate verification probes conducted to verify the effectiveness of the proposed grouting pattern, grouting materials, grout pressure, grout volume intake across depth, sequence and suitability of criteria of cease of grouting. These verification probe tests are needed to ensure that grouted zone is formed as designed. The QP shall determine the required number and depth of verification probes and establish the acceptance criteria. A minimum of 5% of the cavity-treated pile locations is recommended to have verification probes.

8.4 To ensure proper formation of the grout piles, a data logger should be deployed for each grout pile for monitoring and verification purposes. The data logger should minimally log key parameters such as grout pressure, grout volume intake across depth, etc.

8.5 To form grout piles, the tremie displacement method can be deployed using compaction pressure grouting from the cavity bottom. Grouting can be carried out at 0.5 m depth intervals before proceeding to the next 0.5 m layer, as shown in Figure A6.

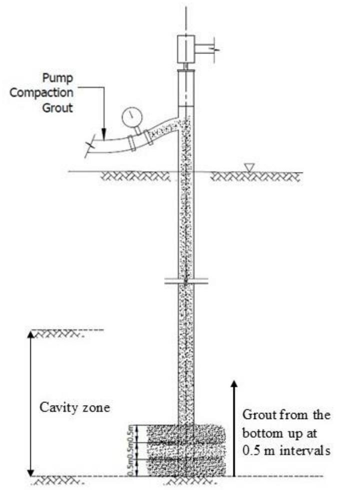


Figure A6 – Compaction pressure grouting using tremie displacement method at 0.5 m depth intervals from bottom up

8.6 Example of cavity grouting by single-point grouting method

8.6.1 If the cavities encountered at the pile locations are small and do not contain much cavity-fill deposits, the single-point grouting method at the pile centre may be adopted. Material selection for cavity filling depends primarily on strength and flowability. Cement mortar should be used for compaction pressure grouting for this case for pre-piling treatment of cavity before commencement of piling installation.

8.6.2 This single-point grouting method involves forming a large diameter grout pile at the pile location, e.g. a minimum 1 m-thick grout barrier with adequate compressive strength formed outside the bored pile perimeter. For example, a 1 m-diameter bored pile requires a minimum 3 m-diameter of grout pile, as illustrated in **Figure A7**. A minimum of 3 verification probes should be conducted at 0.5 m outside the edge of the diameter of bored pile to be formed.

8.7 Example of cavity grouting by multiple-point grouting method

8.7.1 If the area around the piles is ridden with large cavities and/or extensive slump zones, cavity grouting around the pile using compaction pressure grouting may be adopted. This method uses smaller multiple grout piles instead of a single large grout pile.

8.7.2 This treatment method requires the careful planning of the grouting layout to ensure adequate grouting points covering the entire diameter of the bored pile to be installed, as shown in **Figure A8**. A minimum of 3 verification probes should be conducted at the overlapping area of the grout points, an example is shown in **Figure A9**.

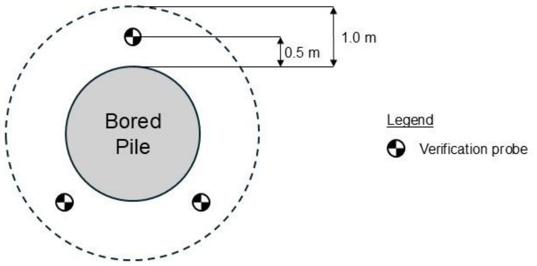


Figure A7 – An example of the single-point grouting method at the pile location

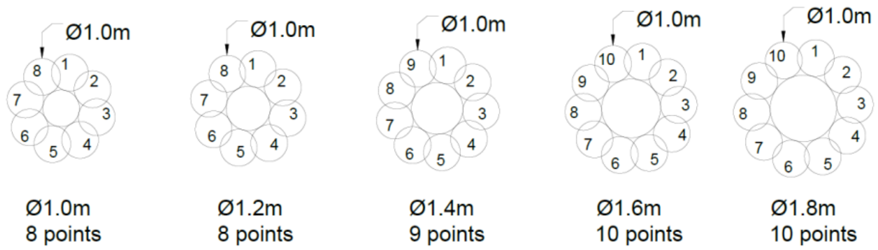


Figure A8 – An example of the grouting layout by the multiple-point grouting method (for bored piles with a diameter ranging from 1.0 m to 1.8 m in the limestone cavity or slump zone)

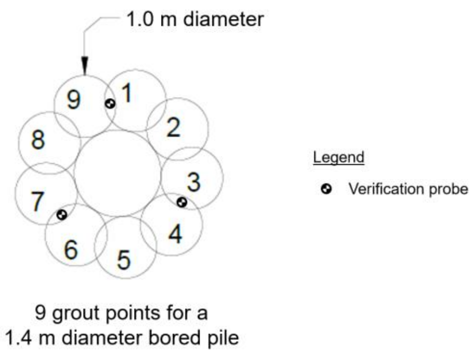


Figure A9 – An example of the grouting layout and location of the verification probes for the multiple-point grouting method for a 1.4 m diameter bored pile

9. Construction of piles in limestone area with cavities

9.1 Unforeseen encounter of cavities during pile boring works

9.1.1 Not all cavities on site may be detected and pre-treated prior to the construction stage. In the event where such cavities are encountered during the pile boring works, on-site mitigation measures should be adopted. Such measures include backfilling with lean concrete (preferred material) or liquefied soil stabiliser (LSS) to stabilise the cavity as illustrated in **Figure A10**.

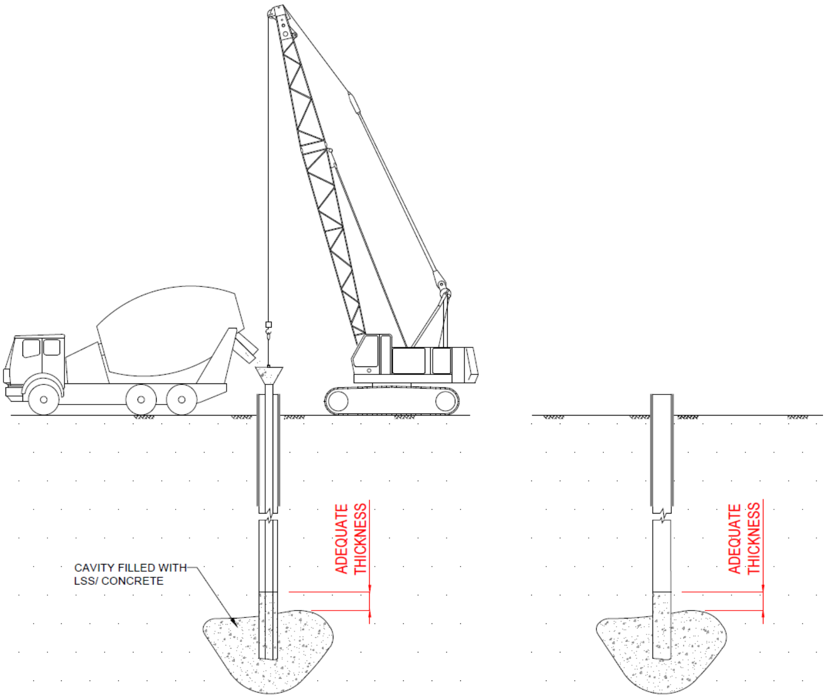


Figure A10 – Cavity backfilling with lean concrete or LSS during pile boring works

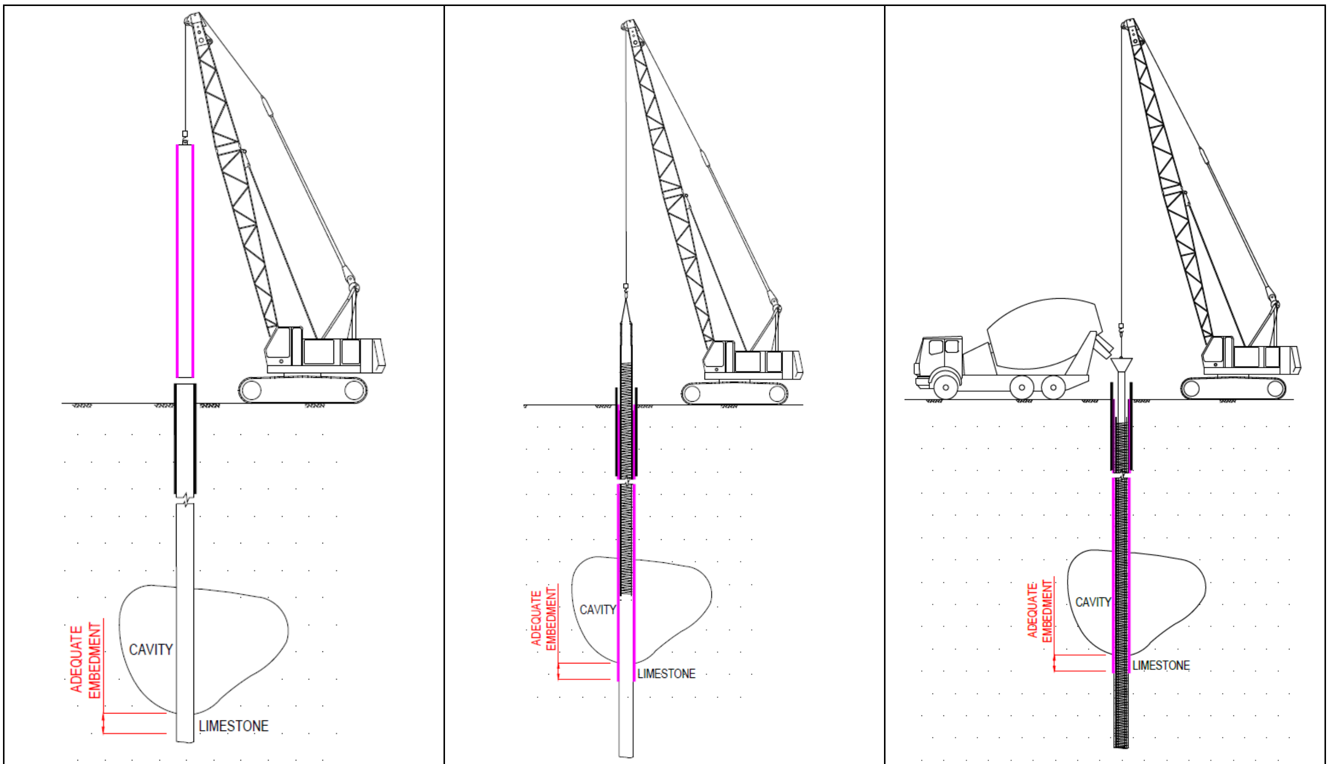
9.1.2 After backfilling, probe holes should be carried out to determine the size and depth of the cavities, followed by cavity treatment prior to the resumption of pile installation works.

9.1.3 A loss of stabilisation fluid or concrete are signs of the presence of cavities. By measuring the volume of the lost fluid and lean concrete, the volume of the cavities can be estimated.

9.2 Permanent steel casing method

9.2.1 A permanent steel casing may be used for ease of pile installation within the cavity zone if the cavities are not pre-treated using compaction grouting. Probe holes should be carried out to determine the size and depth of the cavities in preparation of the required steel casing length (**Figure A11**).

9.2.2 The permanent steel casings should be lowered into the bored hole to the depth where the cavity length has been pre-determined. The permanent steel casing is typically installed to a depth of 0.5 m or 1D, whichever is larger, below the cavity zone of the pile.



Installation of permanent casing through the cavity; Continue drilling to the required pile depth; clean pile toe and confirmed pile toe level.	Lowering steel reinforcement cage.	Concreting the pile.

Figure A11 – Typical procedure for the installation of permanent steel casings

10. Pile testing requirements

10.1 Ultimate load tests should be conducted on piles installed in ground encountering cavities that are treated using the same method as for the working piles, to obtain the representative skin friction and end bearing resistance for a proper design.

10.2 Working load tests should be conducted on onerous pile for each representative zone considering the ground conditions and presence of cavities.

10.3 Pile integrity tests should be conducted on working piles encountering cavities to verify pile shaft has been formed properly without affecting pile structural capacity.

11. Additional ST and as-built submission requirements

11.1 ST submission is required to include the items specified in **Table A6**. If the piles are constructed in accordance with the design principles clearly specified in the drawing, amendment submissions may not be required for piles encountering cavities.

Table A6 – Items required to be included in ST submissions

S/N	Items
1	Locations of the proposed and/or completed boreholes.
2	Locations of the proposed probe holes with termination depths are to be shown on the piling plans.
3	Design principles for determination of the pile termination depth when cavities or slump zones are encountered are to be clearly shown on ST plans.
4	Proposed plan for pre-piling treatment of cavities with detailed material properties, post-treatment verification probes, and typical cavity treatment layout.

11.2 As-built submission is required to include the items specified in **Table A7**.

Table A7 – Items required to be included in as-built submissions

S/N	Items
1	Borehole logs and as-built locations of boreholes.
2	Probe hole logs and as-built locations of probe holes.
3	As-built pile location and depths, including annotation of piles which encountered cavities or slump zones, and design calculations for these piles.
4	As-built pre-piling treatment of cavities. Indicate the depths of the treated cavities, slump zones and permanent casing (if any). Indicate the grout volume intake with depth.

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ANNEX B : GOOD PRACTICES FOR EXECUTING GEOPHYSICAL SURVEYS

1. Geophysical survey methods

Table B1 – A non-exhaustive list of geophysical survey methods for cavity detection, categorised by energy source. Other geophysical methods may be adopted if proven effective.

Energy Source	Geophysical Methods	Standards
Seismic	Seismic Reflection	ASTM D7128-18
	Multi-channel Analysis of Surface Waves (MASW)	ASTM WK89536 (Under development)
	Multi-channel Analysis of Microtremors (MAM)	ISO 24057:2022
	Crosshole Seismic Tomography	ASTM D4428/ D4428M-14
Electric	Electrical Resistivity Tomography (ERT)	ASTM D6431-18; ASTM G57-20
Gravity	Microgravity	ASTM D6430-18

1.1 QPs may refer to ASTM D6429-23 and BS 5930:2015+A1:2020 to determine the usefulness of the respective geophysical methods for cavity detection.

2. Good practices for executing geophysical surveys

(a) A proper desk study of the site and seeking of expert opinion should be completed prior to the conduct of any geophysical survey.

(b) The geophysical survey objectives should be clearly set out at the beginning (e.g. to detect limestone cavities of min. 2 m dimension, up to 100 m depth, etc.).

(c) The appropriate geophysical method(s) should be chosen based on the target features and site conditions. Project parties should be aware of the known method limitations.

(d) The success of the geophysical methods may be site-specific. Consider conducting trial geophysical surveys to assess the method's feasibility and optimise the survey design.

(e) Geophysical methods may provide non-unique solutions, consider adopting diverse methods for cross-validation, and eliminate geophysical models which are not geologically plausible.

(f) An experienced geophysical contractor with proven capabilities and track records should be engaged to design, execute, and interpret the geophysical survey.

3. **Recommended personnel for geophysics workflow**

Table B2 – Types of personnel recommended for each stage of the geophysics workflow

Geophysics Workflow Stage	Level of Expertise
1 Data acquisition	This stage should be led by an experienced geophysicist. This stage needs to be performed locally.
2 Data processing/ inversion	This stage should be performed by a team of experienced geophysicists and/or (applied) physicists or mathematicians. This stage may involve overseas experts.
3 Data interpretation	This stage should be performed by a team of experienced geophysicists/ geoscientists/ geologists/ (applied) physicists or mathematicians. This stage may involve overseas experts, but input from experts who are familiar with the local geology and site conditions will be critical.

Experienced personnel means that the incumbent holds a tertiary degree in the relevant field and possesses at least 3 years of relevant experience since graduation.

ANNEX C: GOOD PRACTICES FOR LIMESTONE CAVITY LOGGING IN BOREHOLES

1. Methods for cavity detection during borehole drilling

Table C1 – A non-exhaustive list of commonly adopted methods for borehole cavity detection in Singapore

S/N	Methods	Method Description
1	Site observations	(a) Sudden drop of drill rods. (b) Loss of water and/or drilling fluid. (c) Abrupt changes in measured drilling parameters (e.g. penetration rate, torque, flush pressure, thrust pressure, etc.).
2	Chemical tests	(a) Perform an acid test on-site to verify the presence of carbonates in the country rock or cavity-infill deposits, in accordance with ISO 14689:2017, Section 5.5. (b) More complex limestone rocks and soils may require further laboratory analyses.
3	Rock core inspection	An experienced geologist should examine the rock core and cavity-fill deposits (if any).
4	Downhole cavity probing	Deploy optical or acoustic televiewers for visual confirmation of any cavities (when necessary).

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2. Good practices for limestone cavity logging in borehole logs

2.1 To standardise the limestone cavity logging practice across the industry, the parameters listed in **Table C2** are recommended to be included in the borehole logs.

Table C2 – List of parameters that are recommended to be recorded in the borehole logs

Parameter	Parameter Description
Geological description of cavities in accordance with Gillespie et al., (2021).	(a) If the cavity is unfilled, report it as a discontinuity, e.g. 'discontinuity type = cavity; filling = none'. (b) If the cavity is filled, report it as a rock type, e.g. 'cavity-fill deposit'. Report any further observations of the cavity-fill deposit. (c) The suspected cause of the cavity should also be reported, where possible.
Cavity depth	Report as 'Cavity from X.XX – X.XX mBGL'. The top depth and bottom depth should be reported to 2 decimal places.
Site observations	Report any: (a) Sudden drop of drill rods: to record the depth of drop. (b) Sudden changes in inclination of drill rods. (c) Water loss: to record the quantity, if possible. (d) No water return. (e) Observed vibrations.
Acid test	Report the observations from any acid tests performed to verify the presence of carbonates in the country rock or cavity-infill deposits in accordance with ISO 14689:2017, Section 5.5.
Photographic evidence	Provide any photographic evidence of the cavity and cavity-fill deposits, where available.

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