

PORT VILA CBD · EFATE · VANUATU

GEOTECHNICAL GUIDANCE HANDBOOK

Building resiliently on Port Vila's ground

A practical guide for planners, engineers, builders and owners to understand the ground beneath the city and build back stronger after the December 2024 earthquake.

HANDBOOK DEVELOPMENT

How this guidance was developed

Prepared as a collaborative effort, led by Port Vila City Council and the Department of Urban Affairs and Planning in response to the December 2024 earthquake.

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1 Introduction

What this section covers

- Purpose of the guidance
- Who this guidance is for
- What this guidance does and does not do
- Background, assumptions and limitations

1.1 Purpose of the guidance

This guidance provides a practical pathway to meeting Vanuatu National Building Code (VNBC) requirements for ground conditions and geohazards in the Port Vila Central Business District (CBD). It sets out expectations for managing the four primary earthquake geohazards (ground shaking, liquefaction, slope instability and fault surface rupture) and provides a common basis for discussion between developers and the approval authority on proposed developments. It draws on the Efate Earthquake Engineering Technical Assistance (EEETA) geotechnical hazard study. The VNBC remains the mandatory legal standard for building work.

This guidance was prepared in response to the December 2024 earthquake, which caused significant damage and loss of life in Port Vila. The earthquake showed the importance of ground conditions, which vary markedly across the CBD, on the observed damage and building performance. Areas founded on reclaimed land and loose soils experienced stronger shaking and ground movement, while buildings on shallow rock generally performed better. Many buildings had not been designed for the ground beneath them or for the level of shaking that occurred. Figure 1.1 shows two examples of the damage.



Figure 1.1 Damage in the Port Vila CBD from the December 2024 earthquake, being structural damage to a commercial building and ground cracking across a reclaimed car park.

THIS GUIDANCE:

- shares the current understanding of the ground conditions in Port Vila.
- sets out which geohazards may be relevant to a site.
- sets out the minimum geotechnical investigation recommended.
- makes clear when a geotechnical specialist should be involved.
- recommends foundation and mitigation options suited to Port Vila's ground and local construction capability.

1.2 Who this guidance is for

Rebuilding and future development of the Port Vila CBD involves a range of parties, whose perspective on ground conditions and geohazards will vary depending on their role or background, and the stage of the project they are at. This guidance has been structured so that each of these parties can use it at the point most relevant to their role. An engineering background is not required to use Sections 1 to 4, whereas Sections 5 to 10 are intended for a more technical audience.

> THIS GUIDANCE IS FOR:
>
> - Landowners and developers needing to understand geotechnical hazards that may apply to their site and what this means for cost, design, and approvals before committing to a project.
> - Approval authority staff needing to check planning permission and building permit applications, set investigation and design conditions, or certify design and construction against the requirements of the VNBC.
> - Design lead and engineers needing to scope and supervise investigations, assess the geohazards, select foundations and mitigation solutions, and verify ground conditions during construction.

For owners and developers, most of the measures in this guidance are more cost effective when they are planned early, and they make it much more likely that a building will remain functional after the next major earthquake.

1.3 What this guidance does and does not do

This guidance:

- explains the four primary earthquake geohazards relevant to the Port Vila CBD (ground shaking, liquefaction, slope instability, and fault surface rupture).
- provides an area-wide understanding of ground conditions, presented as the ground zone and hazard overlay maps.
- describes situations when a geotechnical specialist is strongly recommended.
- sets out minimum geotechnical investigation recommendations by ground zone and building importance level.
- recommends foundation and mitigation options suited to Port Vila.
- supports the planning permission and building permit processes under the VNBC.

This guidance does not:

- replace site-specific investigation and assessment.
- cover every hazard. For example, tsunami and coastal inundation, karst voids, long-term settlement of soft ground, shrink-swell soils, and coastal erosion are potential hazards in Port Vila but sit outside the four geohazards that this guidance covers.
- replace the legally binding VNBC.
- replace good local engineering or construction practices, but aims to enhance them.
- replace detailed design.

1.4 Background, assumptions and limitations

This guidance is based on the EEETA study, which investigated the ground beneath the Port Vila CBD through 2025 and 2026 in more detail than previous studies. The study combined new investigations and historic records into a three-dimensional model of the ground, and the ground zones, hazard overlays and recommendations in this guidance are built on that model. The investigations are summarised below, and the data and interpretation are set out in the supplementary information listed at the end of this section.

NOTES

This study's investigations comprised:

- 11 new machine boreholes with in-situ (in the ground) and laboratory testing.
- 6 downhole geophysical tests.
- 7 km of geophysical survey lines.
- 9 weeks of groundwater monitoring, which captures tidal variation but not the full seasonal range.
- airborne laser scanning (LiDAR) of the study area, compared against 2012 data.
- a review of more than 90 historic investigation records.

KEY THINGS TO KEEP IN MIND WHEN USING THIS GUIDANCE:

- Ground conditions vary between investigation points. A minimum level of investigation is recommended on every site (Section 5). Ground zones provide a high level indication of expected ground conditions.
- Zone boundaries are approximate. Where a site is close to or across a boundary, use the more demanding zone as the starting point (Section 3).
- Outside the study area, the steps in this guidance are still considered good practice, but the ground conditions should be established by site-specific investigation.
- Ground zones and hazard overlays are screening tools. Where a site-specific investigation or assessment has been completed, its findings replace the mapped information as the basis for design at that site.
- Importance levels follow the VNBC (Table A7.1, based on AS/NZS 1170.0). This guidance applies to IL1 to IL4. IL5 facilities require special study beyond this guidance.
- This guidance is written for a broad audience. Technical guidance documents are referenced in the relevant sections.
- This is a living document. Maps and recommendations should be updated as new investigations, monitoring and research are completed. The guidance should also be reviewed after any significant earthquake. Always use the current version, and the digital maps where available.

Supplementary information

This guidance is supported by the following resources, prepared as part of this study:

- Geotechnical factual report: the investigation data from the EEETA study, including borehole logs, in-situ and laboratory test results, geophysical testing, and groundwater monitoring records. Use it when you need the factual data near your site.
- Geotechnical assessment report: the interpretation behind this guidance, including the ground model, how the ground zones and hazard overlays were derived, and the hazard assessments and parameters this guidance summarises. Use it when you need the basis for a mapped boundary, or to review the methodologies and limitations of results when a more detailed analysis could be undertaken.
- Digital map viewer: an interactive web map of the ground zones, hazard overlays and EEETA investigation data, available at www.portvilageohazardviewer.com. Use it to check the zone and overlays at your site before you commission an investigation.

02

2 Establishing the context

What this section covers

- How this guidance fits into the VNBC and the approval process
- Understanding the geohazards
- Ground zones and geohazard overlays

2.1 How this guidance fits into the VNBC and the approval process

The Vanuatu National Building Code (VNBC, 2025 Edition) is the mandatory standard for building work and is empowered by the Building Act 2013. The VNBC sets out the performance requirements that buildings must achieve. This guidance, used alongside other relevant standards and guidance, sets out how to achieve them in the Port Vila CBD, given the city's ground conditions and geohazards. This guidance includes information regarding which maps to check, what geotechnical investigations are recommended, and which foundation and mitigation options are suited to managing the relevant geohazards.

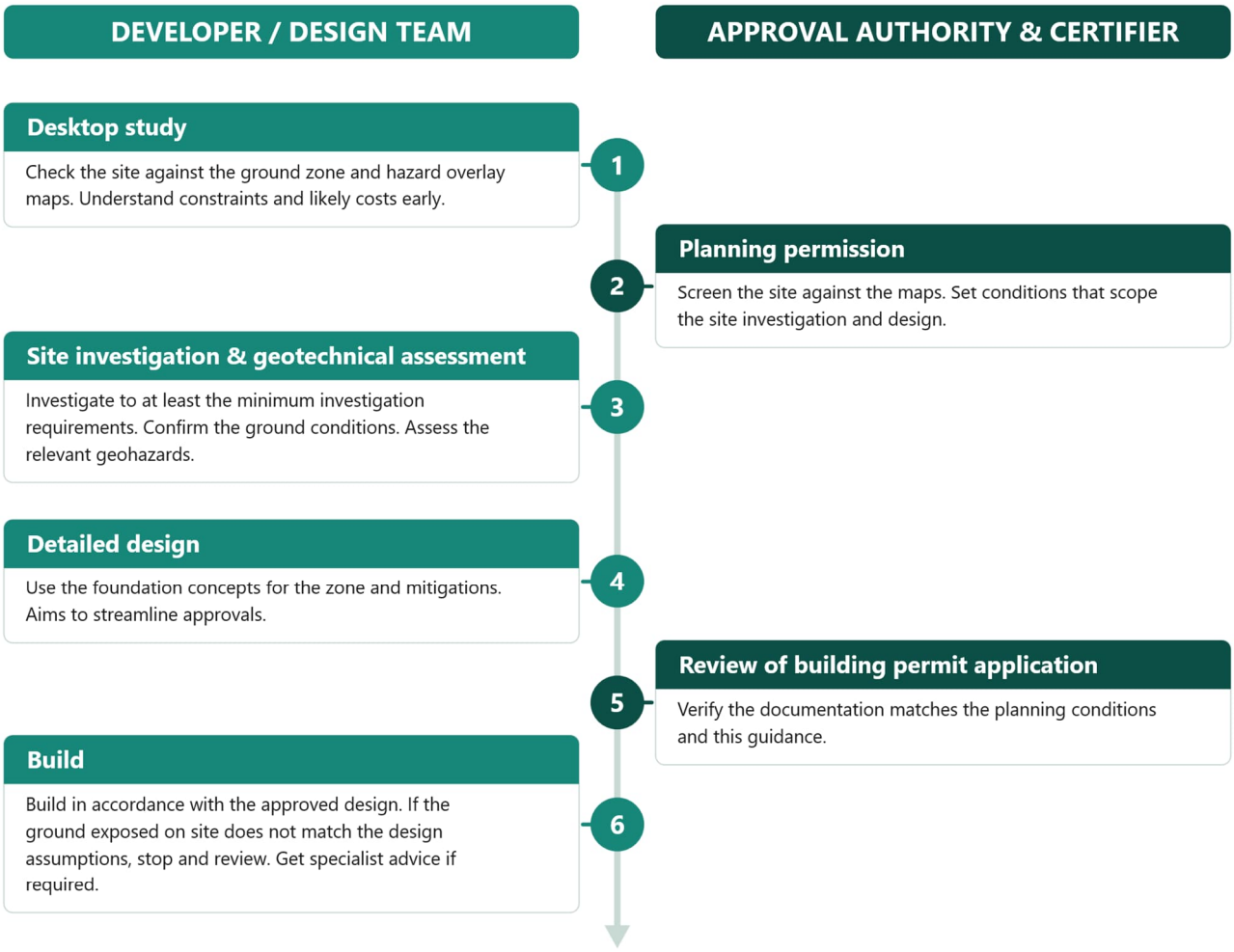
WHAT THE VNBC REQUIRES

- Geotechnical investigation [B3.3]: complex, multi-storey and public buildings of importance level >1 require geotechnical investigation to determine the foundation system. *(Section 5)*
- Good ground [B3.1]: foundations must bear on "good ground" (at least 300 kPa ultimate bearing capacity). Where the site is not good ground, advice from a suitably qualified geotechnical engineer is required for foundation design. *(Sections 4 and 5)*
- Water table [B3.4]: current and future water table depth must be determined, and the adequacy of foundations assessed for changing bearing capacity, heave and buoyancy over time. *(Section 5)*
- Earthquake loading [Section B, B1.3]: every building must be designed for earthquake shaking. IL1 to IL3 buildings to NZS 4203:1992 and IL4 buildings to NZS 1170.5:2004. *(Section 6)*
- Liquefaction [B3.3]: liquefaction potential must be evaluated, settlement estimated, and mitigation or foundation selection proposed. *(Section 7)*
- Sloping ground [B3.2]: where the ground, or adjacent land within 10 m, slopes more than 30°, geotechnical advice is required before foundation design. *(Section 8)*
- Excavations [B1.5]: excavations deeper than 1.5 m must be battered no steeper than 45°, or designed and certified. *(Section 8)*
- Active faults [B3.5]: complex, multi-storey and public buildings of importance level > 1 must not be built within 20 m of an active fault trace, whether known or inferred. *(Section 9)*
- Other geotechnical hazards [B3.5]: complex, multi-storey and public buildings of importance level >1 must not be constructed within known or inferred hazardous geotechnical areas (landslides, cliff collapse, boulder roll, sinkholes and voids) unless specific studies and mitigation measures are in place.
- Foundations and ground conditions [BP3]: foundations must be designed, and ground verified, to prevent damage, collapse and unacceptable movement over the design life. *(Section 10)*

Building work in the Port Vila CBD includes two separate approvals: planning permission and a building permit. In this guidance, the approval authority means the body that assesses the planning permission or building permit application.

Where does this guidance sit in a project timeline?

This guidance applies at every stage of a building project. Figure 2.1 sets out the stages of a typical project.





Note: through Steps 1 to 3, and into detailed design at Step 4, the project layout and the foundation solution can still be readily changed. Changes made later in a project often incur significant cost escalation due to rework.

Figure 2.1 Where this guidance is used through a typical building project.

2.2 Understanding the geohazards

Vanuatu sits on one of the most active plate boundaries in the world and earthquake hazard in Vanuatu is very high by global standards. This is primarily due to the plate boundary along the west coast of Vanuatu, where the Australian Plate dives beneath the Pacific Plate creating the Vanuatu Subduction Zone.

That process lifted Efate out of the sea, incrementally creating the limestone terraces that Port Vila is built on. The same process creates frequent large earthquakes. Since 1907 there have been at least 28 earthquakes of magnitude 7 or greater recorded within 300 km of Port Vila.

The December 2024 earthquake (magnitude 7.3, approximately 25 km from the city at a depth of 54 km) caused significant damage to livelihoods, buildings, and infrastructure. There is a high probability that an earthquake of similar or greater magnitude than the 2002 and 2024 earthquakes will occur within the next 50 years, affecting the Port Vila CBD.

Four primary earthquake geohazards are relevant to the Port Vila CBD, shown together in Figure 2.2. This section explains each one in plain terms.

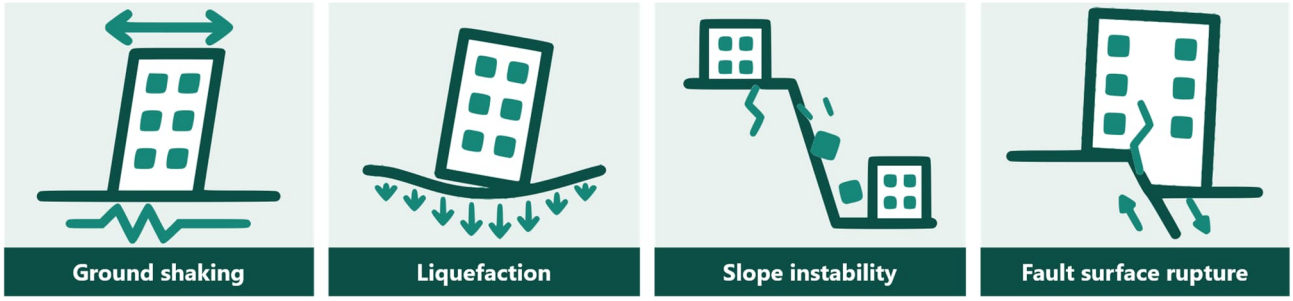


Figure 2.2 The four earthquake geohazards addressed by this guidance.

2.2.1 Ground shaking

The magnitude and duration of shaking felt at a site depends on the earthquake's size, distance and depth, and the ground beneath the site. The ground conditions underlying a site influence the level of shaking that is felt at the ground surface and that experienced by the structure.

The VNBC requires every building in Port Vila to be designed for strong ground shaking. The design shaking is set by the building's importance level and the underlying ground conditions. Figure 2.3 shows how the shaking experienced at a site depends on the distance to the source, the ground, and the building type.

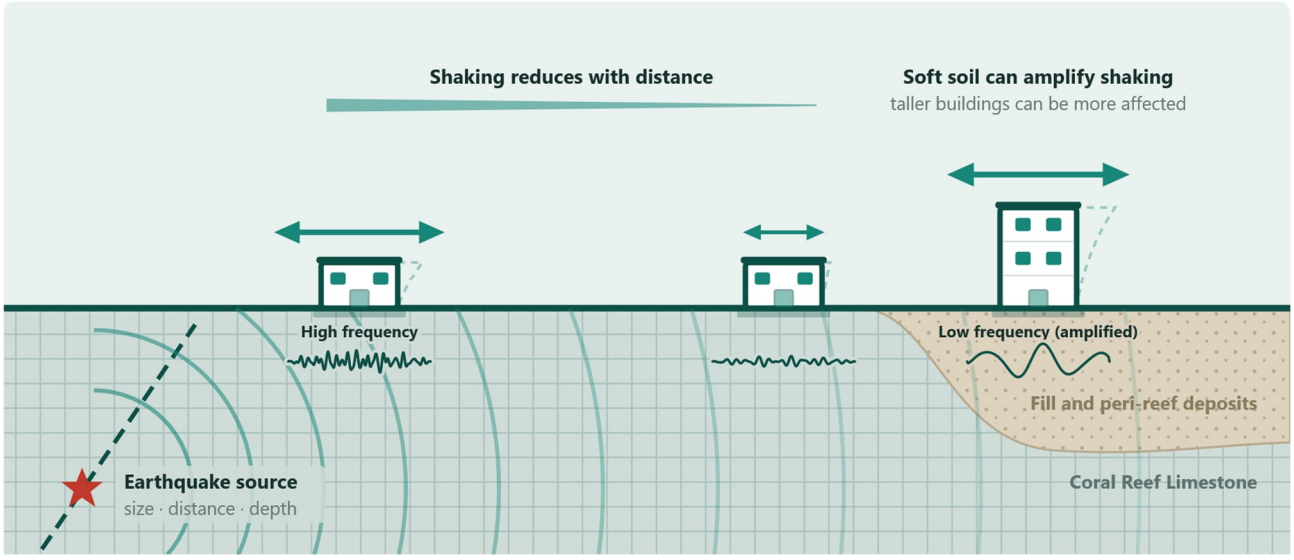


Figure 2.3 Ground shaking. The level of shaking is dependent on the distance to the earthquake source, the ground conditions, and the building type.

2.2.2 Liquefaction

When loose, saturated, sandy ground experiences strong shaking, the water pressure between the individual soil grains rises until the ground temporarily behaves like a fluid. This can cause buildings to settle unevenly and tilt, ground to move sideways towards the sea (lateral spreading), buried tanks to float, and sand to erupt at the ground surface. When the shaking stops, the ground has often settled and cracked. Figure 2.4 shows the mechanism.

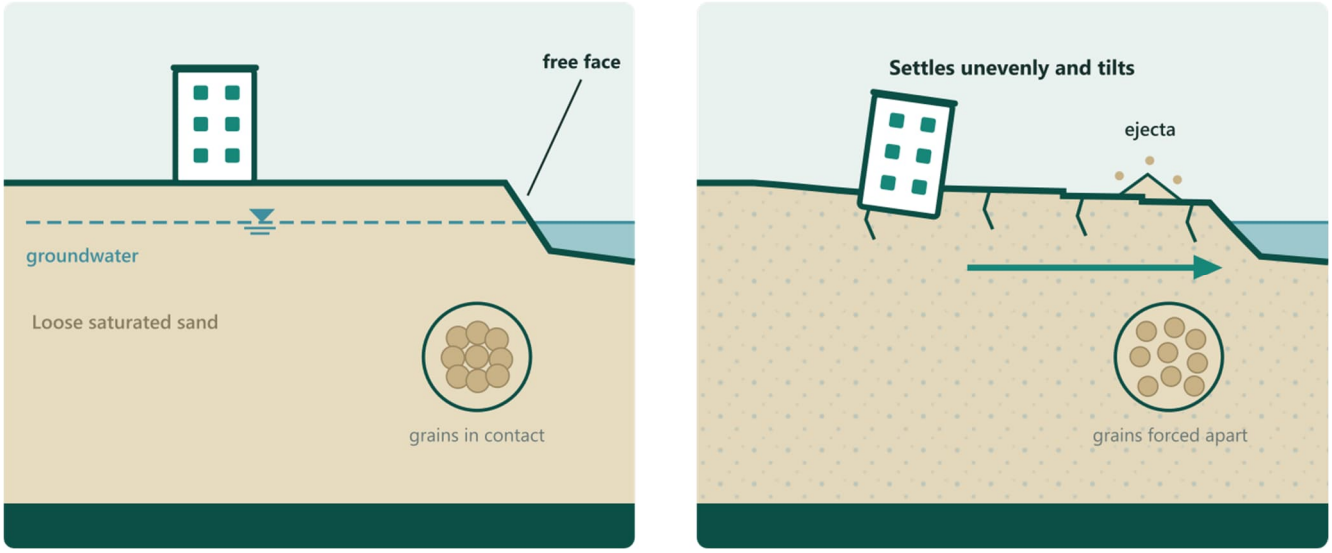


Figure 2.4 Liquefaction. Rising water pressure forces the soil grains apart, so the ground temporarily loses the strength and stiffness that supports the building.

2.2.3 Slope instability

Steep slopes can fail during earthquakes or after heavy rain. During the December 2024 event, the main problem was rockfall and toppling from steep cut slopes and cliff faces. Falling rocks travelled tens of metres, and ground near the top of steep slopes cracked and fell away. Failures were mostly associated with modified slopes, while natural slopes generally performed well. Rockfall and slope regression (such as slumping) are the two mechanisms of slope instability this guidance manages, and Figure 2.5 shows both.

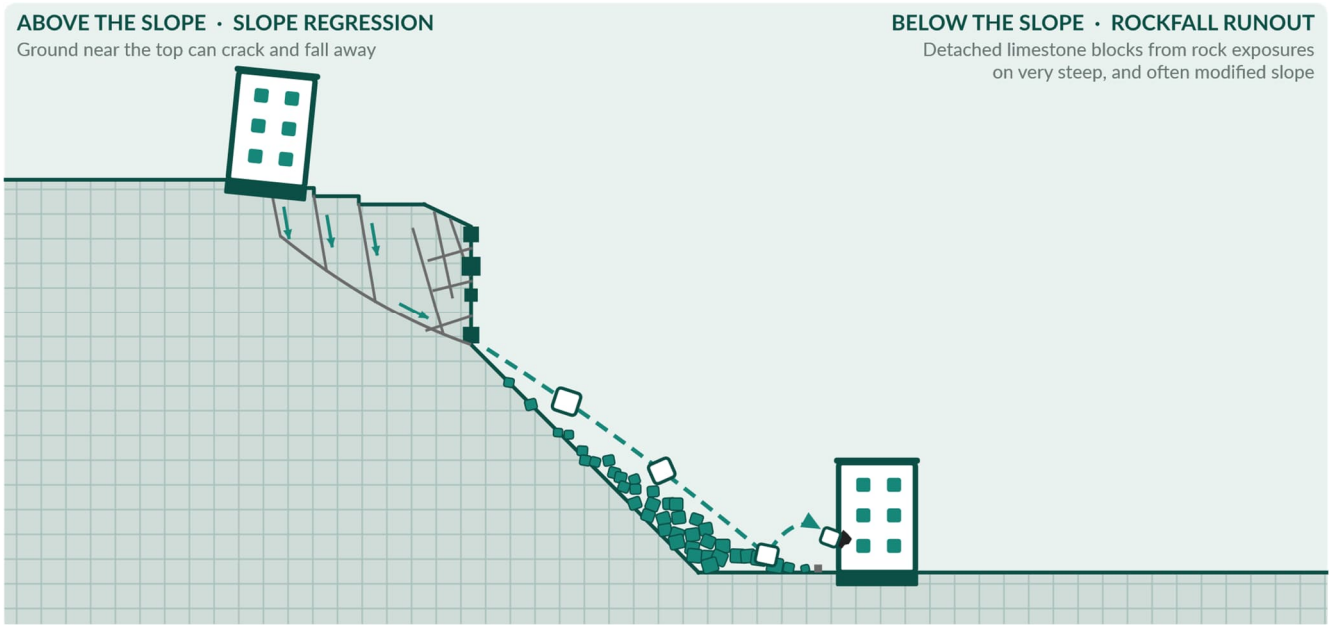


Figure 2.5 Slope instability. Rockfall affects land at the toe of a slope, while slope regression affects land near the crest.

2.2.4 Fault surface rupture

Faults are breaks or zones of weakness in the ground that can move relative to each other during earthquakes. Several fault features cross Port Vila. In December 2024, the ground surface shifted by 100 to 400 mm along two known faults (the Tank Hill and Palace Faults), damaging the buildings that were located on top of the faults. Figure 2.6 shows what happens to a building built across a fault.

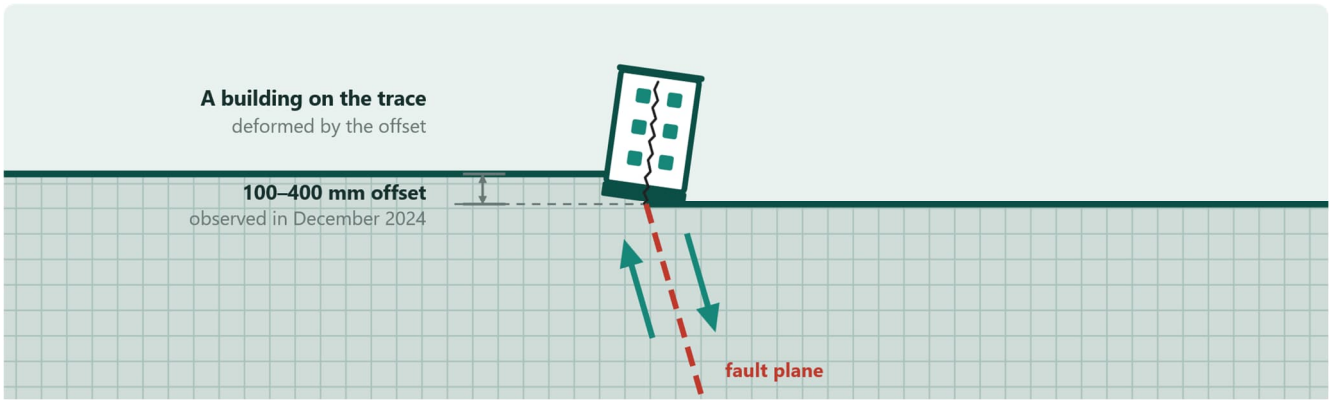


Figure 2.6 Fault surface rupture. Permanent offset of the ground surface tears apart any structure built across the fault.

NON-EARTHQUAKE RELATED GEOTECHNICAL HAZARDS CAN BE EQUALLY IMPORTANT FOR YOUR PROJECT. NON-EARTHQUAKE RELATED GEOTECHNICAL HAZARDS INCLUDE:

- Presence of soft or loose soil that may result in unacceptable building movements over the normal design life of the structure.
- Presence of shallow groundwater and impact on any excavation that extends beneath the groundwater table.
- Uneven ground requiring retaining walls and/or constructed slopes and their associated stability.
- Karstic features in the limestone potentially resulting in sudden, unacceptable building movement.
- Expansive soils, such as the volcanic ash soils near the surface in Zones C and D (Table 2.1), and potential unacceptable deflections to the floor slab and/or foundations.

These are outside the scope of this guidance. These should be assessed by a suitably qualified geotechnical or civil engineer as required.

2.3 Ground zones and geohazard overlays

The Port Vila CBD has been categorised into four ground zones (A to D) with two geohazard overlays. The ground zones describe the expected ground conditions while the overlays identify where the slope and fault hazards exist (the slope susceptibility overlay and the fault deformation overlay). Every site lies within at least one ground zone, and may straddle a zone boundary. A site may also fall within none, one or both geohazard overlays. Figure 2.7 shows a representative ground profile for each zone.

The full-size ground zone and hazard overlay maps are in the digital map viewer (Section 1.4), and the basis for every mapped boundary is set out in the EEETA geotechnical assessment report.

Table 2.1 Ground zones

ZONE	THE GROUND YOU SHOULD EXPECT	WATCH FOR
A	Where lowest, flat reclaimed land along the waterfront Ground 1–6 m loose fill, over 5–20 m coral sands and gravels, over limestone Water 1–2 m below ground level, tidal	• Liquefaction and lateral spreading • *Soft ground settlement* • *Shallow groundwater*
B	Where fringe between the waterfront and the limestone terraces Ground 0–3 m fill over shallow limestone; local sand and gravel pockets to 5 m Water 1–2 m below ground level, tidal	• Localised liquefaction, where sand pockets are present • *Possible soft ground settlement* • *Shallow groundwater*
C	Where central raised limestone terrace Ground 0–2 m ash / fill; limestone within about 3 m Water deep, more than 10 m below ground level	• Typically firmer ground; good ground must still be verified on site • Slope hazards at terrace edges • *Possible karst voids* • *Expansive volcanic soils*
D	Where highest ground Ground 0–2 m ash / fill, over 5–20 m limestone, over Efate Pumice Water very deep	• Typically firmer ground; good ground must still be verified on site • Slope hazards at edges • *Possible karst voids* • *Expansive volcanic soils*

Note: Hazards shown in italics are outside the scope of this guidance. They are listed because they are common in Port Vila and should be considered where relevant, but no assessment or mitigation recommendations are provided. The list is not exhaustive.

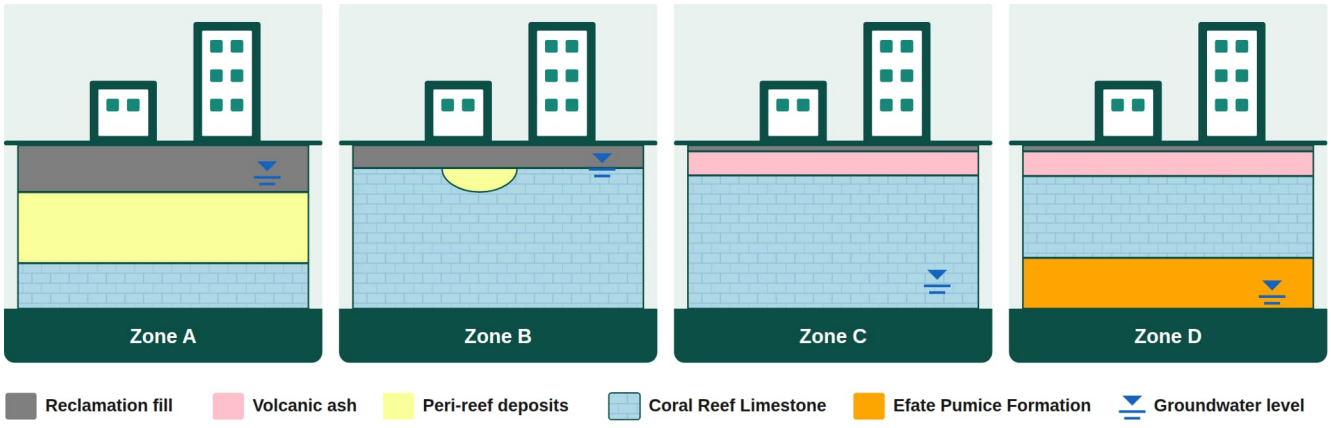
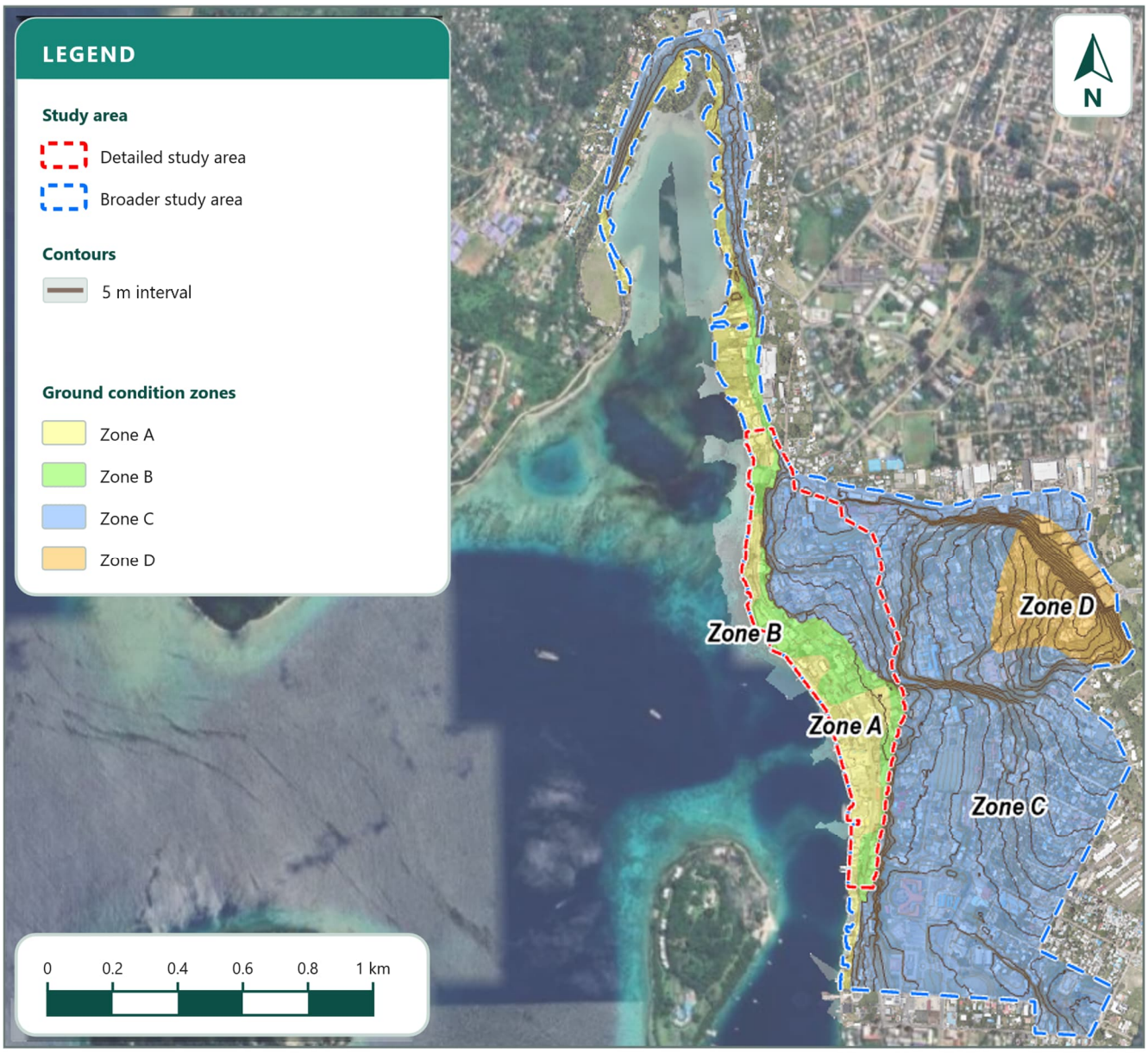


Figure 2.7 Representative ground profile for each ground zone.



Contours from the 2025 Kahuto Pacific LiDAR survey.

Figure 2.8 Ground zone map of the Port Vila CBD. Refer to the digital map viewer for the full-size maps and the hazard overlays.

The slope susceptibility overlay applies where slopes are steeper than about 45° and higher than 4 m. It includes:

- Rockfall runout zones at the base of slopes where falling rocks could reach. High zone (most rocks stop inside it) and medium zone (only a very small fraction of rocks travel this far). Mapped runout distances are typically 10 to 40 m from the slope.
- Slope regression zones at the top of slopes where ground typically within 5 to 15 m of the crest could crack or fall away.

The fault deformation overlay is a corridor along each mapped or inferred active fault, being the greater of 20 m either side of the fault or extended to the crest of a visible escarpment. Inside the corridor, ground movement of 200 to 400 mm in a single event is considered credible.

03

3 Recommended approach to using this guidance

What this section covers

- Overview of the nine-step process
- Project requirements (Steps 1 and 2)
- Site characterisation (Steps 3 to 5)
- Hazard assessment and mitigation (Steps 6 to 9)

3.1 Overview

The process for using this guidance is set out as follows:

- Confirm the project requirements and agree the performance levels (Steps 1 and 2).
- Characterise the ground conditions and identify relevant geohazards (Steps 3 to 5).
- Manage risk to your project through site-specific assessment and design of mitigation measures, as required (Steps 6 to 8).
- Record and agree the residual risk (Step 9).

Figure 3.1 summarises each step in the process and references the section of this guidance that provides the relevant detail.

PROJECT REQUIREMENTS

1 Confirm the project requirements — Section 3.2

Establish the project scope - intended use and occupancy, size and number of levels, possible site layouts, the VNBC requirements that apply, and who is on the project team.

2 Agree the importance level and performance levels — Section 3.2

Classify the building using VNBC Table A7.1, then agree any additional performance requirements with the owner. Together these are the design targets.

SITE CHARACTERISATION

3 Find your ground zone — Section 3.3

Identify the site zone, A to D, from the ground zone map. Where the site is near or across a boundary, adopt the more demanding zone until the investigation shows otherwise.

4 Check the hazard overlays — Section 3.3

Check whether any part of the site falls within the slope susceptibility or fault deformation overlay. Overlays apply on top of the ground zone, so a site can have none, one or both.

5 Complete the minimum geotechnical investigation — Section 5

Investigate to at least the minimum for the ground zone and importance level, to confirm that the ground beneath the site matches the expected ground conditions.

HAZARD ASSESSMENT AND MITIGATION

6 Assess the geohazards — Sections 6–9

Confirm which of the four geohazards apply, then assess the consequence of each for the site and the building as proposed.

7 Compare the effects against the performance levels — Sections 6–10

Where the performance levels are met, record the basis and go to step 9. Where they are not met, go to step 8.

8 Design the response — Sections 6–10

Work through the response hierarchy in order, testing the simplest option first:

- **Avoid.** Move the building, reduce the footprint in the hazard area, or set back.
- **Resist.** Design the structure and foundation to tolerate the ground response.
- **Mitigate.** Improve the ground, or provide protective works.
- **Accept.** Retain the residual risk and record it clearly.

9 Record and agree the residual risk — Sections 6–10

Record what was assessed, what was done and what risk remains, and confirm it between the owner, the design lead and the approval authority.

Figure 3.1 Process for using this guidance.

> **WHEN TO INVOLVE A SPECIALIST**
>
> Engaging a geotechnical specialist is recommended on most projects in the Port Vila CBD. Geotechnical specialist capability in Vanuatu is still developing, technical development of the industry is ongoing, and engaging international specialists may appear cost-prohibitive for some projects. This guidance is therefore structured so that ordinary buildings on straightforward sites can proceed with a competent design team.
>
> Section 4 covers situations where a specialist is strongly recommended.

3.2 Project requirements

3.2.1 Step 1: Confirm the project requirements

Start by establishing the project scope considering the following requirements:

- Project / Building requirements: the intended use and occupancy, the size and number of levels, and the possible site layouts.
- Regulatory requirements: the minimum requirements that apply under the VNBC (refer Table 4.1).
- Project team: the design lead and engineer, and whether a geotechnical specialist should be involved early in the project.

Together these determine how much geotechnical input the project needs, and when.

NOTES

- The most cost-effective hazard management usually happens at this step. Siting and layout decisions made now can often reduce the risk posed by a hazard, or eliminate it entirely, at little or no cost, where the same outcome later requires engineering.
- Several VNBC requirements, such as the mandatory geotechnical investigation for qualifying buildings and the restriction on building near active faults, can affect the design, including the foundation type and any mitigation measures. Confirming them early avoids potential redesign.
- As more information is obtained for the site through the site characterisation and hazard assessment stages, the project team may need to reassess the agreed performance levels for the project.

3.2.2 Step 2: Agree the importance level and performance levels

Classify the building using VNBC Table A7.1, adopting the highest applicable level where a building has more than one use. Then consider with the owner any additional performance requirements or site constraints that may influence the design (beyond the VNBC importance level requirements). These may include:

- Settlement requirements, particularly for buildings that may have low tolerance for ground settlement, such as factories with sensitive machinery.
- Functionality of the building for moderate earthquakes.

The importance level, the building typology, and the performance levels influence the geotechnical investigation scope, the level of geotechnical assessment, and the design response.

THE BUILDING IMPORTANCE LEVELS IN VNBC TABLE A7.1 CAN BE SUMMARISED AS FOLLOWS:

- IL1 – minor buildings, such as sheds and outbuildings. Design target: No dangerous collapse.
- IL2 – normal buildings, such as most houses, shops and offices. This is the default for most CBD sites. Design target: Life safety, with damage accepted but no collapse.
- IL3 – major or community buildings, such as schools, markets and assembly buildings. Design target: Operational after an earthquake.
- IL4 – post-disaster buildings, such as hospitals, fire stations and emergency services. Design target: Fully operational after an earthquake.
- IL5 – critical facilities. These sit outside this guidance and need a site-specific specialist study.

NOTES

- The importance level should be identified before the investigation scope is fixed. If the importance level is set too low early in the process, the site may be under-investigated and additional investigation work may be required later.
- The importance level also affects decisions such as:
  - whether a residual hazard is acceptable,
  - how much redundancy or robustness is needed in the design of the foundation system,
  - whether avoidance is more appropriate than mitigation, and
  - what level of post-earthquake function is expected.
- The importance level describes the consequence of failure, not how heavily the building loads the ground or how much movement it can tolerate. A five-storey residential apartment with capacity less than 1000 people or where less than 300 people can congregate in an area, and a single-storey shop are both IL2, yet they place very different demands on the foundations.
- Record the building typology with the importance level: number of storeys, structural form, indicative foundation loads, any basement or below-ground level, and the differential settlement the structure can tolerate.

3.3 Site characterisation

3.3.1 Step 3: Find your ground zone

Identify your site's zone (A to D) from the ground zone map in Figure 2.8, or from the digital map viewer, together with the descriptions in Table 2.1. The zone indicates the expected ground profile, the likely groundwater setting, and the hazards most likely to require attention, before any investigation is scoped. If the site is close to a zone boundary, or the building footprint crosses one, adopt the more demanding zone until the site investigation shows otherwise.

Where these checks are completed early, unsuitable concepts can generally be ruled out before significant expenditure is committed to detailed design.

THE GROUND ZONE FOR THE SITE SETS THE EXPECTED GROUND PROFILE FOR THE PROJECT.

- For Zone A – expect loose, wet soils that are susceptible to liquefaction, to depths of 10 to 20 m.
- For Zone B – expect shallow limestone rock but possibility of localised loose soils that are susceptible to liquefaction.
- For Zones C and D – ground is generally good. Expect shallow limestone rock.

NOTES

- The ground zone maps do not indicate:
  - The exact depth to good bearing material across the site.
  - Any undocumented fill.
  - Whether there are karst voids beneath the site.
- Beware of building footprints or site boundaries that cross the ground zone boundaries or are very near the ground zone boundary. For these sites it is important that additional geotechnical investigations are carried out to confirm the ground zone and relevant geohazards.
- Nearby earthquake damage may suggest locally weaker ground conditions are present, which are not included in the maps.

This is why a minimum level of geotechnical investigation is recommended.

3.3.2 Step 4: Check the hazard overlays

Check whether any part of the site falls within the slope susceptibility overlay or the fault deformation overlay. Overlays apply in combination with the ground zone, so a site can have none, one or both. An overlay adds a hazard to assess and potentially manage in design. It does not prohibit building. The overlays are not exact lines on the ground, so where a site is close to a boundary, the hazard should be considered in this assessment. Figure 3.2 shows how the overlays are checked across a site.

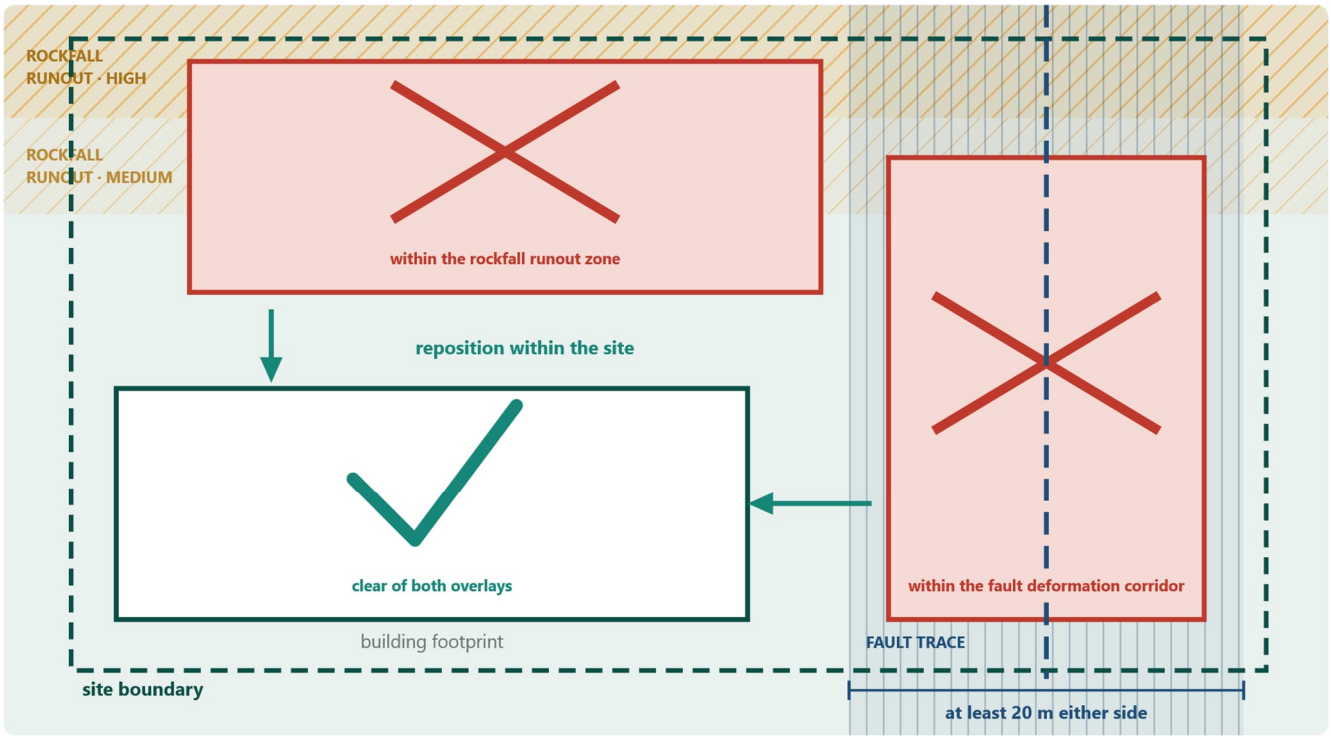


Figure 3.2 Checking the hazard overlays across a site. Overlay boundaries are indicative. Repositioning the building within the site is often the simplest response.

SLOPE SUSCEPTIBILITY ZONES ARE MAPPED AROUND SLOPES STEEPER THAN APPROXIMATELY 45° AND HIGHER THAN 4 M, AND CAPTURE TWO MAIN TYPES OF SLOPE HAZARD:

- Rockfall runout at the base of slopes, falling rocks can reach the land at the toe of the slope.
- Slope regression at the crest, ground near the top of the slope can crack and fall away during shaking or later weathering.

FAULT DEFORMATION OVERLAY CORRIDORS ARE MAPPED ALONG KNOWN OR INFERRED ACTIVE FAULTS, WITH:

- Corridor width of at least 20 m either side of the fault, or to the crest of an escarpment where that is wider.
- Ground movement within the corridor estimated to be of the order of 200 to 400 mm in a single event.

NOTES

- Often the most cost-effective and proportionate way to manage a geohazard is to avoid or reduce its effects through the site layout, including the placement of buildings, infrastructure, and site access.
- While a site may be within a slope susceptibility zone, it does not mean every part of the site is equally hazardous. Setting buildings and infrastructure back from the toe of the slope (in relation to rockfall risk) or from the crest (in relation to slope regression risk) is often a practical way to reduce the effects of the hazard.

3.3.3 Step 5: Complete the minimum geotechnical investigation

A site walkover and a review of existing data are recommended on every site, in every zone. Beyond that, the method, density and depth of the investigation are informed by the ground zone and the building importance level. The core purpose of the investigations is to characterise the ground conditions beneath the site to support robust design.

THE INVESTIGATION CONFIRMS OR REVISES THE EXPECTED GROUND CONDITIONS. ON EVERY SITE, ESTABLISH:

- Fill – whether it is present, and how thick it is.
- Loose sand or peri-reef deposits – whether they are present.
- Bearing stratum – the depth to it, and the nature of it.
- Groundwater – the likely level, and whether it is shallower than expected.

Where the ground encountered differs from the mapped zone, revise the ground model and revisit Steps 1 to 4 before design proceeds.

NOTES

- Investigation effort should increase with the uncertainty in the ground conditions and with the complexity and importance level of the proposed development. An IL4 building in Zone C will need more investigation than a small IL2 building on the same ground to provide confidence that the structure will perform as anticipated.
- A zone described as generally good ground still needs investigation. Good ground at city scale can contain local variation at building scale.
- A single historical borehole on a neighbouring site does not define the ground conditions for your site. It can be helpful, but it does not replace site-specific investigation.
- Undertake a more thorough investigation where the site sits near a zone boundary, where unexpected loose sand, soft fill or shallow groundwater is found, or where neighbouring buildings, or the previous building on the site, showed strong damage in the December 2024 earthquake.
- Sites within the slope susceptibility zones and fault deformation overlay have specific investigation recommendations outlined in Section 8 and Section 9 respectively.

3.4 Hazard assessment and mitigation

3.4.1 Step 6: Assess the geohazards

This step uses the site investigation to refine the area-wide understanding from the maps into a site-specific assessment, so your design reflects the ground behaviour and geohazards expected at your site. Review the applicable geohazard modules in Sections 6 to 9. Each module summarises:

- the outcome of the EEETA area-wide assessment,
- the recommended site-specific assessment process to estimate the consequence of applicable hazards at your site (for example, how far falling rocks could reach), and
- example mitigation options for managing the hazard.

GEOHAZARDS TO ASSESS, BY GROUND ZONE AND OVERLAY:

- Ground shaking – assess on every site, in every ground zone.
- Liquefaction – assess in Zone A, and in Zone B where the investigation finds loose sand pockets. Generally not expected in Zones C and D.
- Slope instability – assess where any part of the site falls in a slope susceptibility zone, or lies close to a steep slope.
- Fault surface rupture – assess any part of the site that falls within the fault deformation overlay.

NOTES

- Match the level of assessment to the site and the building. Start with a screening check and increase the detail of the assessment where the screening shows the hazard matters.
- Level of assessment can be balanced against the level of conservatism in design. A simple IL2 building may adopt a foundation that tolerates the expected ground movement instead of a more rigorous assessment. On sites where specialist involvement is strongly recommended (Zone A, Zone B (liquefaction), a hazard overlay, or an IL3 or IL4 building), discuss this trade-off with the specialist, and record the basis for any decision in the building permit application.
- The zones and overlays set the minimum scope. If your site observations identify the potential for a hazard the maps do not show, assess it. Examples: a Zone C site close to an unmapped cut slope, or a Zone B site with a thicker loose sand pocket than expected.
- Geohazards outside the four that this guidance focuses on can still affect a site, such as karst voids, long-term settlement, coastal erosion, and tsunami inundation. They sit outside the scope of this guidance, and should be assessed separately.
- Recording the hazards that do not apply is as useful to the approval authority as recording those that do. For example, a Zone A site where the investigation confirms shallow limestone across the footprint, with no loose sand or fill above it, may not need further liquefaction assessment.

3.4.2 Step 7: Compare the effects against the performance levels

Compare the hazard estimates from Step 6 against the performance levels agreed at Step 2, for the building as currently proposed. The comparison decides whether a design response is needed to achieve the design target.

THE COMPARISON HAS TWO OUTCOMES:

- Performance levels met – the design can proceed without geohazard-specific measures. Record the basis for that conclusion, then go to Step 9.
- Performance levels not met – go to Step 8 and design a response, testing the simplest option first.

NOTES

Meeting the performance levels does not mean there is nothing to do. The foundation still has to be designed for the ground conditions found at the site. It means that no geohazard-specific measures are needed beyond ordinary design.

3.4.3 Step 8: Design the response

Where the performance levels are not met, design a response. Work through the response hierarchy in order, testing the simplest option first. A complex engineering solution should not be the starting point where a modest change in location or layout would remove the problem.

THE RESPONSE HIERARCHY, IN ORDER OF PREFERENCE:

- Avoid – move the building, reduce the footprint in the hazard area, or set back from the hazard where practicable, such as relocating a building outside a fault overlay.
- Resist – design the structure and foundation to tolerate the ground response, such as a robust, well-tied together foundation to tolerate differential settlement.
- Mitigate – improve the ground, or provide protective works, to reduce the hazard, such as a catch ditch to intercept rockfall.
- Accept – retain the remaining residual risk and record it clearly.

NOTES

- Many sites use more than one response. Examples below:
  - A building might be moved back from the steepest part of a slope (avoid), then founded on a robust tied foundation for the remaining uneven ground movement (resist).
  - A rockfall fence could add protection (mitigate) to a building, with a small residual risk of rockfall impacting the structure recorded (accept).
- The chosen response should be buildable in Port Vila. A solution that cannot be built, inspected or maintained reliably is not appropriate, so choose the response as a project team given local constraints. For example:
  - Liquefaction – whether the expected settlement, tilt or lateral movement, for the building as proposed, still allows the target performance to be met.
  - Slope instability – whether the rockfall or crest regression exposure is low enough, or whether the building should be moved.
  - Fault surface rupture – whether any part of the building would remain in the fault deformation overlay, and if so, what permanent ground movement the design would need to tolerate.
- Where the response still does not meet the agreed performance levels, return to the site layout or reconsider the location of the project. The performance levels can also be revisited with the owner and the approval authority, as at Step 2.

3.4.4 Step 9: Record and agree the residual risk

Record what was assessed, what was done, and what risk remains, in plain terms, so that the owner, design lead, and approval authority share the same understanding.

FOR EACH GEOHAZARD ASSESSED, THE FOLLOWING SHOULD BE RECORDED:

- The site-specific issue – what the investigation and assessment found.
- The response adopted – what the design does about it.
- The residual risk – what remains once that mitigation is in place.
- The acceptance – the remaining residual risk has been confirmed between the owner, design lead, and approval authority.
- The construction check – the conditions under which work pauses if the ground exposed during construction does not match the design assumptions.

The record forms part of the building permit application, so that the approval authority can confirm this process has been followed.

NOTES

- The question this record answers is: after the chosen response is applied, is the remaining likelihood and consequence of harmful ground behaviour low enough for this building and this use?
- Describe the residual risk in terms the owner can act on: what could happen, how likely it is, and what it would mean for the building and its use.
- Examples of remaining residual risk:
- some repairable post-earthquake settlement may still occur, without collapse;
- a low rockfall exposure remains in very rare events;
- the risk to the building footprint is reduced to low, and the fault deformation overlay remains across the unused part of the lot.
- Record the residual risk even where it is low, so that the acceptance is explicit rather than assumed.

04

4 When a geotechnical specialist is required

What this section covers

- Who does what?
- What "suitably qualified geotechnical specialist" means
- When specialist involvement is strongly recommended
- What the specialist should provide

4.1 Who does what?

This guidance refers to three project roles. On a small project, one person may hold more than one role, but the responsibilities of each role stay distinct.

- Approval authority staff: set investigation and minimum design requirements where appropriate, and certify design and construction against the requirements of the VNBC.
- Design lead: the person responsible for the building design as a whole, and for making sure the steps in this guidance are completed. On many Port Vila projects this is the architect or the lead engineer who is responsible for the structural and geotechnical aspects of the project.
- Geotechnical specialist: a suitably qualified geotechnical specialist, as described in Section 4.2. A geotechnical specialist should be engaged where the ground conditions or the type of building carry a higher geotechnical risk than the design lead can reasonably manage using this guidance alone.

4.2 What "suitably qualified geotechnical specialist" means

When applying this guidance, a suitably qualified geotechnical specialist is a Chartered Professional Engineer with geotechnical experience, or an engineer with relevant geotechnical experience working under the supervision of such a person (for example Engineering New Zealand CPEng). An equivalent international professional registration may also be appropriate. Where the VNBC requires advice, design or certification from a suitably qualified geotechnical engineer or a Professional Consultant (Table 4.1), the person must be a Professional Consultant as defined in the VNBC.

A geotechnical specialist should have a sound understanding of site investigations, behaviour of the underlying ground conditions, foundation performance, and the earthquake geohazards relevant to Port Vila. They should also be able to explain the limits of the available information and the consequences for design.

For some projects, local site work may be combined with review by a suitably qualified specialist located outside Vanuatu. This is common practice and is appropriate provided the specialist has enough information to take responsibility for the advice given. In practice, this may mean local logging, testing, and construction observation supported by offshore technical review and sign-off.

WHAT THE VNBC REQUIRES

A3.1 Definitions (extract)

"Professional Consultant – a person with appropriate experience, qualifications, and specialization in the relevant field, being:

- An Approved Person practicing in Vanuatu; or
- Registered on the National Engineering Register (NER) of the Institution of Engineers Australia and is an Approved Person; or
- Registered under the Registration Authority for Chartered Professional Engineer, New Zealand and is an Approved Person; or
- Registered as a Professional Engineer in the United States and is an Approved Person."

4.3 When specialist involvement is strongly recommended

Engaging a geotechnical specialist is good practice on every project. The ground zone and overlay maps give you a starting point. They do not replace the site-specific judgement needed where ground conditions change over short distances, which they do across much of the CBD.

Geotechnical capability in Vanuatu is still developing and this will be a long-term process. Bringing in an international specialist can be cost-prohibitive on a smaller project. This guidance therefore identifies where specialist involvement matters most, so that the cost of specialist advice is proportionate to the risk being managed.

The VNBC sets out most of the situations where geotechnical advice is required. Table 4.1 summarises these VNBC requirements, together with the additional situations where this guidance recommends engaging a geotechnical specialist.

Table 4.1 When geotechnical advice is mandatory under the VNBC, and when this guidance recommends specialist input

WHAT THE VNBC REQUIRES *geotechnical advice is mandatory in these situations*	VNBC Ref.
☐ The site is not founded on "good ground" Geotechnical advice is required from a suitably qualified geotechnical engineer (*Professional Consultant*) for the design of the foundation system.	VNBC B3.1
☐ The ground on site, or adjacent land within 10 m of the proposed foundations slopes more than 30° Advice is required before any foundation element is designed or installed. Even slopes some distance from the foundations can affect them if they become unstable.	VNBC B3.2
☐ Batters on an excavation deeper than 1.5 m and greater than 45° on any side Must be designed and certified by a Professional Consultant.	VNBC B1.5
☐ A complex, multi-storey or public building (IL > 1) within 20 m of an active fault, known or inferred The building shall not be constructed within this zone. Consult the Vanuatu Meteorology and Geohazards Department for fault information and to obtain necessary development permissions. Advice shall be sought from a suitably qualified geotechnical engineer (*Professional Consultant*).	VNBC B3.5
☐ A complex, multi-storey or public building (IL > 1) in a known or inferred hazardous area: landslide, mass movement, cliff collapse, boulder roll, sinkholes or voids. The building shall not be constructed where these hazards apply unless specific studies and mitigation measures are in place. Consult the Vanuatu Meteorology and Geohazards Department. Advice shall be sought from a suitably qualified geotechnical engineer (*Professional Consultant*).	VNBC B3.5

WHAT THIS GUIDANCE ADDS *specialist input strongly recommended*		
☐	The building is complex or multi-storey, and situated in Zone A or Zone B Liquefiable soils and complex ground conditions require specialist assessment and foundation selection.	*this guidance*
☐	The building is more than 3 storeys	*this guidance*
☐	The building is IL3 or IL4 Higher consequence of failure demands more confidence in the ground model and the design response.	*this guidance*
☐	The site straddles ground zones, or is located close to a zone boundary The ground may differ significantly across building footprints.	*this guidance*
☐	The ground encountered does not match the design assumptions, or does not fit any described ground zone For example, deep or soft fill, cavities, groundwater seepage or loose soils. The ground model needs revising and the design amended before work proceeds.	*this guidance*

4.4 What the specialist should provide

The geotechnical investigation and assessment provide the inputs that the structural engineer needs to design both the foundations and the superstructure. At minimum, that geotechnical work should produce:

- a site-specific interpretation of the ground conditions relative to the zone maps, including the investigation logs and the surveyed location and ground level of each investigation point.
- an assessment of the geohazards that apply to the site, and mitigation options where necessary, together with identification of any hazards not covered by this guidance that may affect the site.
- foundation assessment that includes:
  - bearing capacity or founding recommendations.
  - estimated total and differential settlement.
  - the site subsoil class.
- any site-specific seismic design parameters needed for the project.
- any additional geotechnical or construction considerations pertaining to the development, such as excavations, groundwater etc.

This information should be provided as a signed report that addresses each of the items listed above, to support the building permit application. The report should contain a level of detail matched to the project and be written so it is usable by more than one audience. The report should give the design lead enough technical direction to complete the foundation and structural design, and give the approval authority and the building certifier enough information to understand the geotechnical basis of the design submitted for the building permit.

NOTES

- The structural engineer uses the outputs from the geotechnical investigation and assessment to design the building in accordance with the VNBC and AS/NZS 1170 framework. For this guidance, that means NZS 4203:1992 under the VNBC path for IL1 to IL3, and NZS 1170.5:2004 for IL4, together with the related structural loading standards.
- Early coordination between the geotechnical and structural engineers is essential. This is especially important on Zone A sites and within the hazard overlays, where the project may need to balance life-safety performance, repairability, construction cost, and what can realistically be built in Port Vila.
- For IL3 and IL4 buildings within a hazard overlay, an independent review of the geotechnical report is recommended.

05

5 Minimum geotechnical investigation recommendations

What this section covers

- Purpose and context for geotechnical investigation
- Investigation methods
- Minimum investigation recommendations by zone and importance level

5.1 Purpose and context for geotechnical investigation

This section sets the minimum geotechnical investigation expected for each ground zone and each building importance level. The investigation should do two things:

- check whether the ground conditions at the site align with the mapped zone, and
- collect enough information to assess the geohazards and design the foundation.

Where the site is variable, close to a zone boundary, affected by a hazard overlay, or proposed for a complex or high-consequence building, the scope should be increased beyond the minimum. Where the investigation shows that the ground conditions differ from the mapped zone, the assessment and design should be based on the conditions found at the site, not the mapped zone.

The investigation recommendations in this section give effect to the following VNBC requirements.

WHAT THE VNBC REQUIRES

B3.3 Foundation Design (extract)

“For complex and multi-storey buildings and public buildings of importance factor > 1: mandatory geotechnical investigation and geotechnical tests must be undertaken to determine the foundation systems…”

B3.1 General Requirements (extract)

“The ground upon which the foundations are bearing shall be good ground…”

B3.4 Water Table Rise

“The existing water table depth, projections of future water table depth due to climate change/sea level rise and other factors, and the current and future salinity of the water shall be determined. The adequacy of foundations shall be assessed, and investigations performed as required to determine if the ultimate and allowable bearing capacity will change over time, if heave/buoyancy will occur.”

THE METHOD, DENSITY, AND DEPTH OF INVESTIGATION SHOULD INCREASE WITH:

- the uncertainty in the ground conditions at the site, and
- the importance level of the building.

This means that an IL4 building in Zone C may require more investigation than a small IL2 building in the same zone, even though both are on generally good ground. It also means that a Zone A site generally requires a more extensive investigation than a Zone C site for the same building type.

5.2 Investigation methods

The main investigation methods, and their benefits and limitations, are set out below in Figure 5.1 and Table 5.1. Minimum investigation depths are given in Section 5.3.

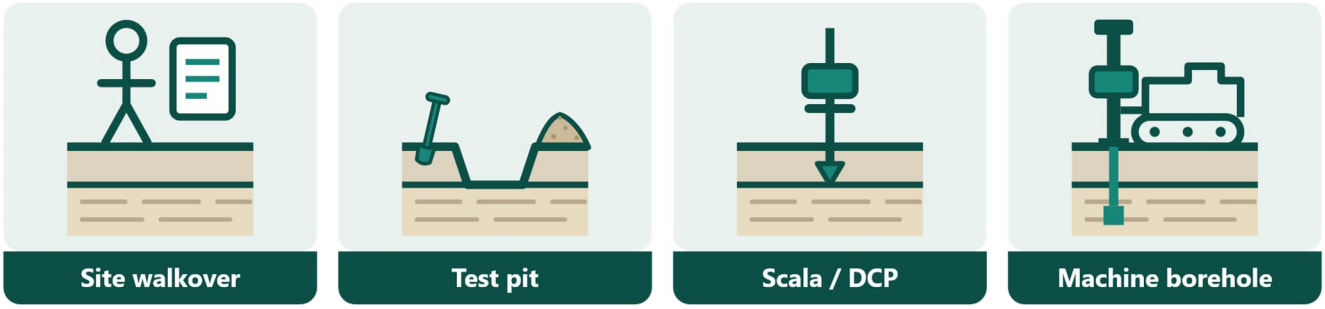


Figure 5.1 Common geotechnical investigation methods available in Port Vila.

Table 5.1 Common geotechnical investigation methods available in Port Vila

METHOD	DESCRIPTION AND BENEFITS	MAIN LIMITATIONS
Site walkover *first step at every site*	Record evidence of fill, cracks, settlement in nearby structures, seepage, slope hazards and retaining walls, on and around the site.	No physical observation of the ground beneath the site.
Test pits *hand-dug or machine · to about 3 m*	Quickest and cheapest way to see shallow ground directly: fill thickness, shallow ash or limestone, groundwater, and variability across the site.	Depth limited by access, groundwater and excavation safety. Poorly compacted backfill can settle.
Scala penetrometer / Dynamic Cone Penetrometer *to about 4 m in soft soils*	Quick, portable check of resistance with depth in fill, ash and soft sandy soils. Suits multiple test positions across a site.	No samples recovered. Refusal (the probe cannot be driven deeper) can occur early in gravel, coral, very dense layers or limestone.
Machine borehole with Standard Penetration Test *Typically 15 to 30 m*	The key method for the deeper reclaimed and loose deposits (Zone A, parts of Zone B), liquefaction assessment, and confirming founding conditions for heavily loaded or high importance level structures.	Limited availability of equipment in Port Vila; programme drilling early.

NOTES

Previously collected data from adjacent sites can reduce the amount of new investigation needed, but it should not replace a walkover and investigation on the actual site. Previously collected data that may assist includes:

- EEETA investigation data (Refer https://portvilageohazardviewer.com/).
- Historical project boreholes or test pits.
- Nearby foundation excavations.
- Previous geotechnical reports.

These data can help inform the new investigation and avoid repeat work but they are still indirect evidence. Ground conditions can change over short distances, especially in reclaimed ground, local sand pockets, terrace edges, and disturbed sites.

Test pits deeper than 1.5 m must meet the VNBC excavation safety requirements [B1.5].

Machine borehole availability in Port Vila is limited, so drilling should be programmed early.

5.3 Minimum investigation density by zone and importance level

The investigation scope should meet at least the minimum recommendations in Table 5.2, which are set by ground zone, development size and importance level. Investigations are classed by depth as follows:

- Shallow investigations: test pits, DCPs or shallow boreholes, to at least 3 m below ground level and at least twice the expected foundation width below the base of the foundation. Shallow boreholes are useful where test pits are impractical, such as where groundwater is shallow or ground disturbance is not acceptable.
- Deep investigations: machine boreholes, to at least 15 m below ground level or at least 3 m into competent ground that can support the foundations (such as limestone rock), whichever is reached first.

THESE ARE MINIMUM RECOMMENDATIONS ONLY AND SITE-SPECIFIC ASSESSMENT MAY BE NEEDED TO CONFIRM THE REQUIRED INVESTIGATIONS IF:

- deep foundations are required.
- the proposed building or structure is heavy or irregular, or has deep excavations or retaining walls (e.g., building greater than 5 storeys, dams, bridges, ports, canals).
- the site is close to a zone boundary.
- the site is inside a slope susceptibility zone or fault deformation overlay.
- the ground has been cut, filled or reworked.
- the initial investigation finds unexpected variability, or the site observations do not match the mapped zone.

Table 5.2 Recommended minimum density of geotechnical investigation for detailed design and the building permit application

ZONE	CATEGORY	IL2 *normal*	IL3 *major*	IL4 *post-disaster*
A	Up to 3 storeys and less than 1000 m²	• 4 shallow investigations	• 2 deep + 4 shallow investigations	• 3 deep + 4 shallow investigations
	More than 3 storeys or ground floor area more than 1000 m²	• 2 deep + 4 shallow investigations	• 4 deep + 4 shallow investigations	• 5 deep + 6 shallow investigations
B	Up to 3 storeys and less than 1000 m²	• 4 shallow investigations[1]	• 4 shallow investigations[1]	• 4 shallow investigations[1]
	More than 3 storeys or ground floor area more than 1000 m²	• 2 deep + 4 shallow investigations	• 2 deep + 4 shallow investigations	• 3 deep + 6 shallow investigations
C	Up to 3 storeys and less than 1000 m²	• 2 shallow investigations[1]	• 3 shallow investigations[1]	• 4 shallow investigations[1]
	More than 3 storeys or ground floor area more than 1000 m²	• 2 deep + 4 shallow investigations	• 2 deep + 5 shallow investigations	• 3 deep + 6 shallow investigations
D	Up to 3 storeys and less than 1000 m²	• 2 shallow investigations[1]	• 3 shallow investigations[1]	• 4 shallow investigations[1]
	More than 3 storeys or ground floor area more than 1000 m²	• 2 deep + 4 shallow investigations	• 2 deep + 5 shallow investigations	• 3 deep + 6 shallow investigations

Notes:
[1] If limestone is not encountered in the test pits, at least one borehole is recommended to confirm the depth to limestone.
[2] A site walkover and a review of existing information (Table 5.1) are recommended on every site, in addition to the locations shown.
[3] In addition to the number, the spatial arrangement of investigations should be such that the site is adequately characterised.
[4] For buildings with a ground floor area greater than 1000 m², at least one additional deep and one additional shallow investigation should be undertaken for each 500 m² of building footprint in excess of 1000 m².
[5] Where one borehole is recommended, it should be placed to test the likely least favourable or most variable ground conditions.
[6] If shallow investigations refuse on limestone, coral gravel or another hard layer, the reason for refusal should be logged. Good ground should not be assumed without sufficient evidence.

SCOPING DEPTH OF INVESTIGATION TO ASSESS GEOHAZARDS AND FOUNDATION DESIGN

- Earthquake Geotechnical Engineering Practice Module 2, Section 2.4.4 (MBIE/NZGS, 2021)

06

6 Ground shaking

The VNBC requires all buildings in Port Vila to be designed for earthquake-induced ground shaking.

Potential ground shaking intensity at a site is uncertain. Port Vila and Vanuatu are in a region that is highly seismically active and complex and the understanding of ground shaking hazard is evolving rapidly as more information becomes available.

While uncertainty in ground shaking cannot be avoided, uncertainty in ground and building performance can be controlled through good design practice.

WHAT THE VNBC REQUIRES

The VNBC sets the earthquake-induced loading by importance level as follows:

- IL1 to IL3 buildings are designed to NZS 4203:1992 with a zone factor of 0.7 for Port Vila, using the standard's site categories (rock or very stiff soil; intermediate; flexible or deep soil).
- IL4 buildings are designed to NZS 1170.5:2004 with a hazard factor of 0.7, using site classes A/B (rock), C (shallow soil), D (deep or soft soil) and E (very soft soil).

A site-specific seismic hazard study may be used to set the design earthquake loads, but those loads must not be lower than the loads calculated using the code's minimum hazard factor of 0.7.

NOTES

As part of the EEETA programme, a seismic hazard assessment (SHA) has been undertaken for Port Vila CBD. The SHA estimates future levels of ground shaking for Port Vila by considering the likelihood of earthquake ruptures, the level of shaking due to any one rupture and the influence of local ground conditions on ground shaking. The SHA undertaken for Port Vila CBD uses a mathematical model to combine all possible earthquake ruptures relevant for Port Vila to estimate ground shaking and the likelihood of occurrence.

The ground shaking levels from the SHA for Port Vila CBD are generally significantly higher than the values required to be considered in the VNBC. The VNBC refers to New Zealand standards that are now significantly outdated. Nevertheless, it is acknowledged that the loading estimated in the SHA may not be practical or economic to design to, particularly for IL1 to IL3 structures.

The level of ground shaking to be used in design should be agreed between the owner and the design engineer when setting the performance levels for the project. Designing to the VNBC minimum generally costs less up front, but the building is more likely to be damaged in a major earthquake. Designing to the higher SHA shaking (or somewhere in between) costs more, but reduces the likelihood of damage and downtime after a major earthquake. For IL4 buildings in particular, performance expectations post a major earthquake should consider current understanding of seismic hazard in Port Vila.

Given the high ground shaking hazard in Port Vila CBD, it is generally recommended that substructure and foundation elements are tied together where possible to promote uniform behaviour.

GUIDANCE ON GOOD EARTHQUAKE ENGINEERING DESIGN PRACTICE TO ACCOMMODATE UNCERTAINTY IN GROUND SHAKING

- Earthquake Design for Uncertainty prepared by NZSEE (August 2022).

07

7 Liquefaction

What this section covers

- Where it applies
- Assessment methodology
- High-level mitigation strategy

7.1 Where it applies

Liquefaction hazard is important to consider if your project is within Zone A or Zone B. It can result in significant reduction in strength and stiffness of the underlying soil leading to many damaging consequences.

Susceptibility differs between the two zones:

- Zone A: Loose fill, typically 1–6 m thick, overlies coral sands and gravels, with tidal groundwater about 1–2 m below the surface. Widespread liquefaction should be expected in strong shaking, and the proximity of the coastal free face means lateral spreading is also a key consideration for sites near the waterfront.
- Zone B: Fill is thinner over shallow limestone, and tidal groundwater sits at a similar level, about 1–2 m below the surface. Localised sand and gravel pockets can be present to about 5 m depth, although shallow fill directly over limestone rock is more common. Where pockets do occur, liquefaction is typically confined to these pockets, and geotechnical investigation is needed to confirm whether they are present beneath your site.

Liquefaction is generally not a concern in Zones C and D, where the groundwater table is deep and limestone is close to the surface. These zone boundaries form the initial screening criteria for liquefaction hazard.

> WHAT THE VNBC REQUIRES
>
> B3.3 Foundation Design (extract)
>
> “Liquefaction potential shall be evaluated, identified, settlements/upheave estimated, and mitigation measures and/or appropriate foundation selection proposed as part of the geotechnical investigation and tests.”

7.2 Assessment methodology

A general approach for assessment of liquefaction potential is provided below and summarised in Figure 7.3. The three key steps for a liquefaction assessment are:

- Assessment of liquefaction susceptibility. Saturated sand, non-plastic silt and gravel mixtures are susceptible to liquefaction.
- Assessment of liquefaction triggering. Liquefaction triggering is dependent on the density of the susceptible soils and level of ground shaking for your project.
- Assessment of liquefaction consequence. Liquefaction consequence, such as ground settlement and lateral spreading, depends on the extent of liquefaction triggering, presence of free-face (such as coastal seawalls) and distance between this free-face and your building, and the size and weight of your building.

Figure 7.1 provides a conceptual illustration of ground and building deformation due to liquefaction. Broadly the liquefaction-induced mechanisms are:

a. Ground settlement and building tilting due to consolidation as the hydraulic pressure gradient generated by liquefaction dissipates.
b. Ground settlement and building tilting due to reduction in ground strength immediately beneath the foundation, resulting in 'punching' of the building into the ground.
c. Ground settlement and building tilting due to a building 'ratcheting' into the softened ground.
d. Ground settlement and building tilting due to liquefied soil escaping as 'ejecta' at ground surface resulting in loss of ground beneath building.

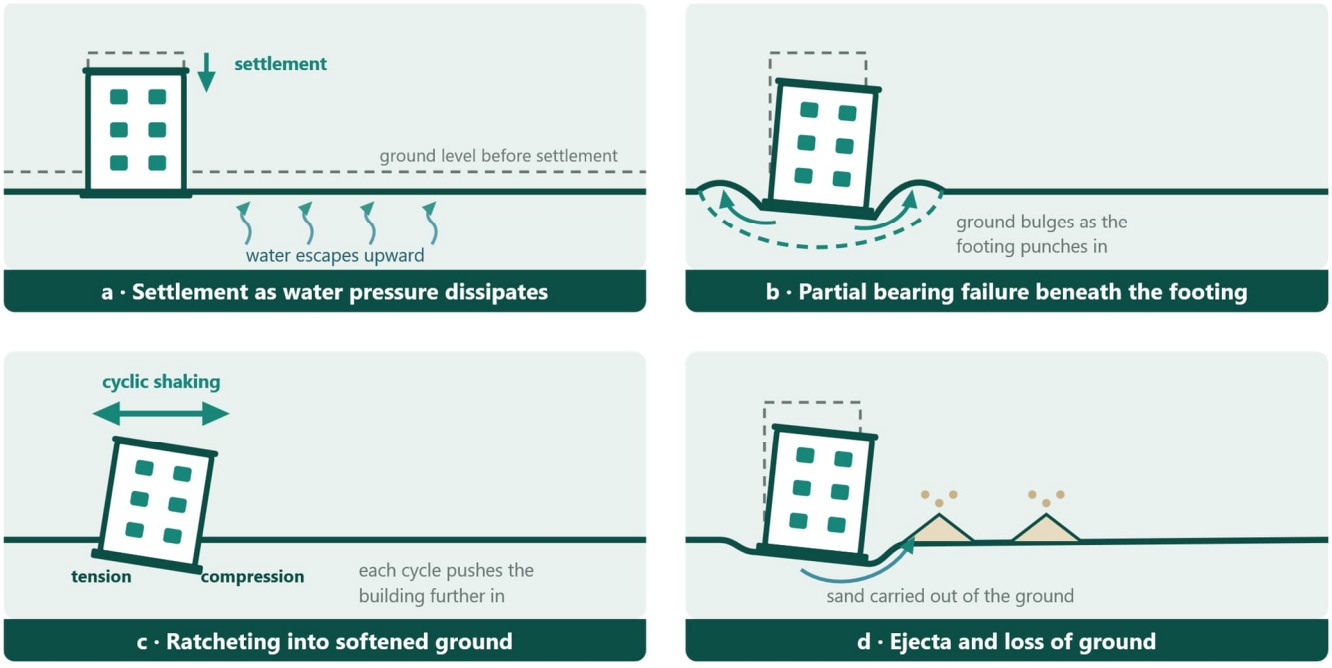


Figure 7.1 Liquefaction-induced building deformation mechanisms, based on Bray and Dashti (2014) and Bray and Macedo (2017).

Figure 7.2 provides a conceptual illustration of lateral spreading towards a 'free face' and lateral stretch across a building that can result in cracking.

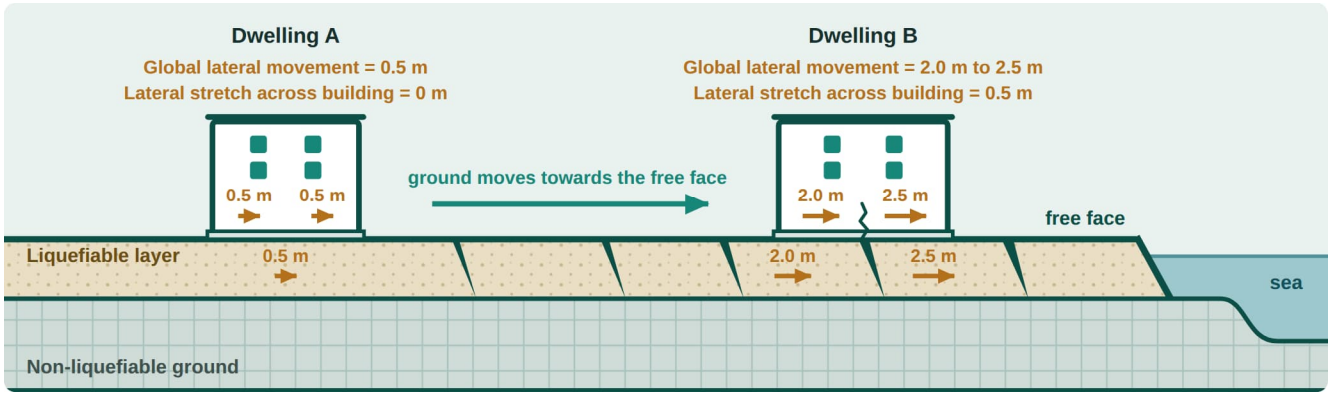


Figure 7.2 Simplified illustration of lateral spreading towards a free face and the concept of lateral stretch across a building.

The consequences of the liquefaction-induced mechanisms in Figures 7.1 and 7.2 on built structures can vary from minor to severe damage depending on the extent of liquefaction, location of the structure near the coast, and the ability of the structure to accommodate ground movement.

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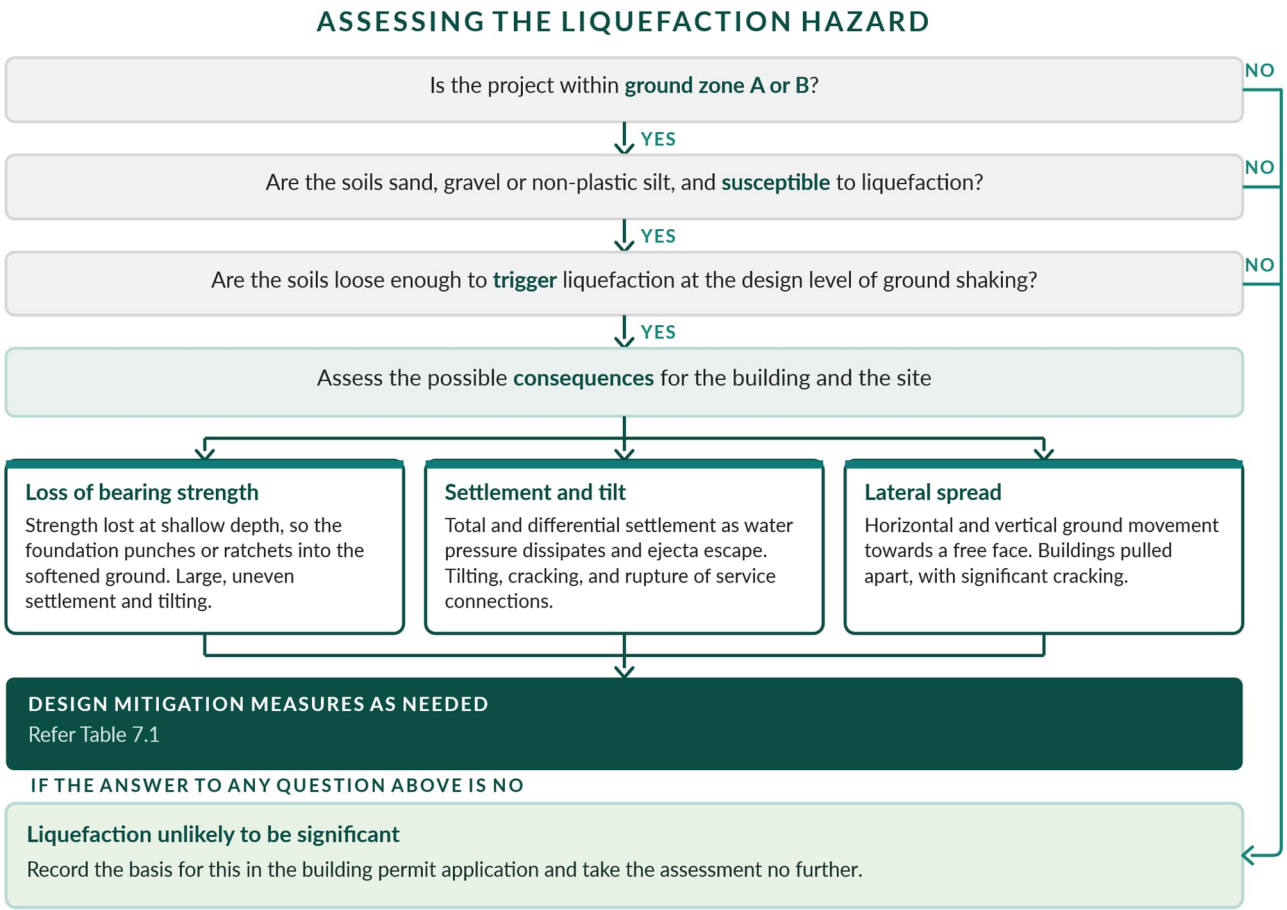


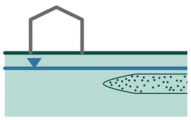
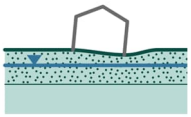
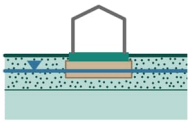
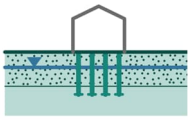
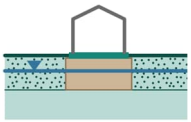
Figure 7.3 Liquefaction assessment methodology.

It is important that the potential impact of liquefaction is considered for all projects. However, the level of analytical effort is likely to vary depending on the importance and value of the project. For example, for lightweight single-storey structures, the assessment may be limited to confirming the ground zone and selecting a foundation system that is more tolerant to ground settlement. For projects of higher value or importance, site-specific investigations and quantitative assessments are recommended.

7.3 High-level mitigation strategy

The mitigation strategies to manage liquefaction-induced consequences will be informed by the performance requirements for your project and building. Table 7.1 provides high-level mitigation options to manage the liquefaction hazard.

Table 7.1 High-level mitigation options for managing the liquefaction hazard

	OPTION	ADVANTAGES	LIMITATIONS	UPFRONT COST
	**Avoid** Place the building footprint clear of liquefiable soils within the site, where the hazard is localised. Zone B, for example, may contain pockets rather than continuous layers.	Moves away from the hazard instead of designing for it. Likely to reduce foundation costs, and improves post-earthquake resilience where the other hazards are managed.	Needs enough investigation to find and map the liquefiable soils, and room on the site to avoid. Not an option where the liquefiable soils run across the entire site.	nil
	**Accept liquefaction effects** Accept that ground settlement and building cracking may occur, provided there is no life safety risk. Repair likely needed to return to functionality.	Likely to be the lowest cost option. Can be suitable for IL1 and IL2 lightweight buildings that can tolerate ground deformation and be repaired after an earthquake.	Costly repairs may be needed to return more significant buildings to functionality. Important to confirm liquefaction-induced settlement and loss of bearing support do not create a life safety risk.	nil
	**Limited ground improvement and/or well-tied foundation** Reduce differential settlement with a well-tied together foundation, limited ground improvement, or both.	Most practical for one to three storey buildings where some residual movement can be tolerated. More resilient than the 'Accept' option to smaller but more frequent earthquakes.	Some settlement due to liquefaction is still likely. The building may need re-levelling after a significant earthquake.	low–medium
	**Piled foundations** Transfer the building loads through the liquefiable soils to competent founding material below.	Likely to be more practical for heavier buildings and higher consequence structures.	Piles need to be designed for the effects of liquefaction. May be costly for lower importance structures, and may not suit areas subject to lateral spreading.	medium
	**Ground improvement** Treat the potentially liquefiable soil itself, by ground improvement methods including densification, replacement, solidification or reinforcement.	Shallow foundations can usually be supported over the improved ground. Increased resilience post-earthquake provided other hazards are suitably mitigated. Robust against lateral spread.	Can be very expensive. Requires specialist machinery and construction control.	high

DETAILED GUIDANCE FOR ASSESSMENT OF LIQUEFACTION SUSCEPTIBILITY, TRIGGERING, AND CONSEQUENCE:

- Geotechnical Earthquake Engineering by Steven L. Kramer and Jonathan P. Stewart (2025)
- Monograph on Soil Liquefaction during Earthquakes by Idriss I. M. and Boulanger R. W. (2008)
- Earthquake Geotechnical Engineering Practice: Module 3. Identification, assessment and mitigation of liquefaction hazards by New Zealand Ministry of Business, Innovation and Employment and New Zealand Geotechnical Society (2021)

This guidance does not cover potential reduction in strength and stiffness of the ground due to mechanisms other than liquefaction (such as cyclic softening).

08

8 Slope instability

What this section covers

- Where it applies
- Assessment methodology
- High-level management strategy

8.1 Where it applies

The main slope hazard is rockfall and toppling from steep limestone slopes, rather than broad deep-seated landslides across the whole city.

The slope susceptibility zones are mapped around slopes steeper than about 45° and higher than about 4 m, and comprise:

- Rockfall runout (below slopes): the hazard is impact from rocks that detach from the slope face and fall, topple or roll downslope. Runout is separated into two susceptibility zones:
  - High: the ground closest to the base of the slope, out to a 36° angle measured down from the top of the rockfall source (see note below on runout envelopes), where most fallen rocks come to rest and debris is thickest near the toe. Structures here are likely to be heavily impacted or in some instances buried during a major event.
  - Medium: the band of ground further out, between the 36° angle and a flatter 29° angle, both measured down from the top of the rockfall source, reached by only a small proportion of fallen rocks. Impacts here are less frequent and more likely to be individual rock strikes to structures.
- Slope regression (above slopes): the hazard is progressive retreat of the crest as rocks detach and fall away. The zone extends about 5 to 15 m back from the crest; at the edge, ground and the support it provides to structures can be lost entirely, grading back to cracking and minor slumping further from the edge.

For screening purposes, the 29° runout envelope should be adopted as the extent of potential rockfall runout, i.e. both the High and Medium susceptibility zones should be treated as potentially affected. The distinction between the two zones indicates the relative likelihood and severity of impact, not whether assessment is required. Accordingly, if structures are to be built within these zones, a site-specific assessment is recommended before considering mitigation measures. Figure 8.1 shows the runout envelope below a slope and the regression envelope behind the crest.

NOTES

- Runout envelope: This is the land downslope of a landslide source area, which can be inundated with debris when a landslide occurs. Its extent is set by the angle measured from the top (crest) of the slope down to the furthest point the debris reaches. A steeper angle (36°) stays closer to the slope and contains most fallen rocks; a flatter angle (29°) reaches further out, to where only a few rocks travel. Specialists refer to this as the Fahrböschung or travel angle.
- Regression envelope: This is the area typically upslope of a potential rockfall source area or over-steepened slope, where ground deformation could be expected due to block drop out or tilting.

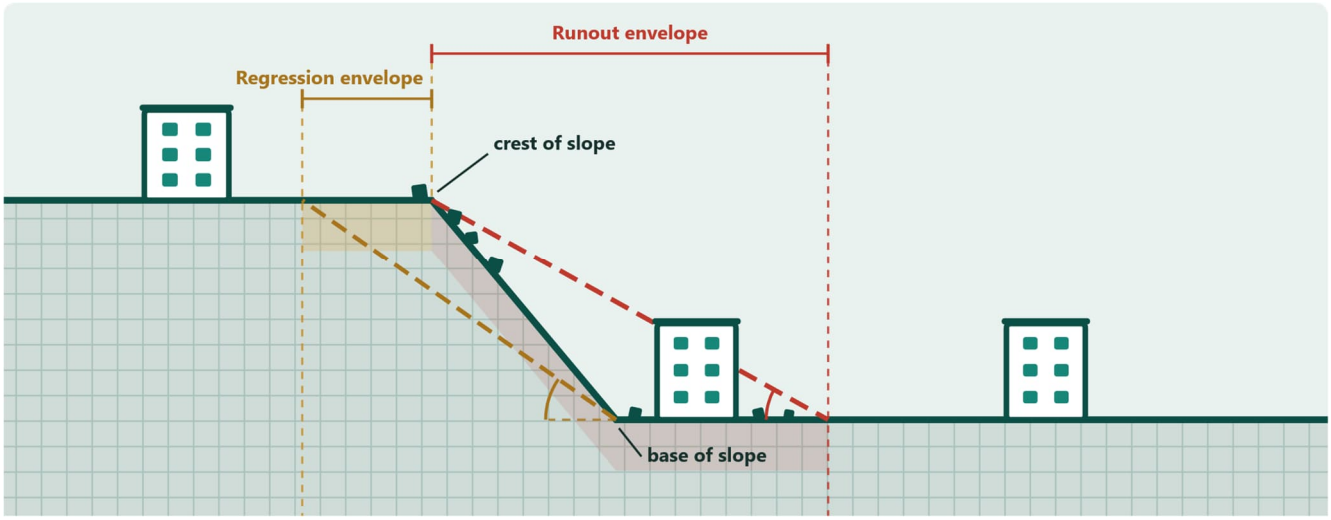


Figure 8.1 Slope instability, showing the rockfall runout envelope below the slope and the slope regression envelope behind the crest.

WHAT THE VNBC REQUIRES

B3.2 Sloping Ground

"Where a building is to be constructed on sloping ground, due consideration shall be given to the stability of the ground under loading from the structure. The verticality of foundation elements shall be maintained, and the slope shall be battered and benched as required. Refer to Part B1.5 for excavation limitations including depth and batter requirements.

If the ground is sloped at greater than 30º from the horizontal, advice shall be sought from a suitable qualified geotechnical engineer (Professional Consultant) prior to the design and installation of any foundation element.

The potential for landslide and land slip often extends beyond the land immediately under the building. Where the adjacent land is sloped at greater than 30º from the horizontal in any location within 10 m of the proposed foundations of the building, advice shall be sought from a suitable qualified geotechnical engineer (Professional Consultant) prior to the design and installation of any foundation element."

B1.5 Excavations

"The following criteria for all excavations must be satisfied.

- Excavations greater than 1.5 m deep must be either: battered back with a slope no greater than 45° on all sides; or designed and certified by a professional consultant.
- Excavations must be set back a minimum of 1.5 m from any property boundary and batter away from the boundary with a slope of no greater than 45° unless specific permission is granted by the local authority."

B3.5 Other Geotechnical Hazards (extract)

"Construction Near Landslides, Land Mass Movements, Cliff Collapse, Boulder Roll Areas, and Sinkholes/Caves/Voids: complex and multi-storey buildings and public buildings of importance factor > 1 shall not be constructed within hazardous geotechnical areas known or inferred, unless specific studies and mitigation measures are in place."

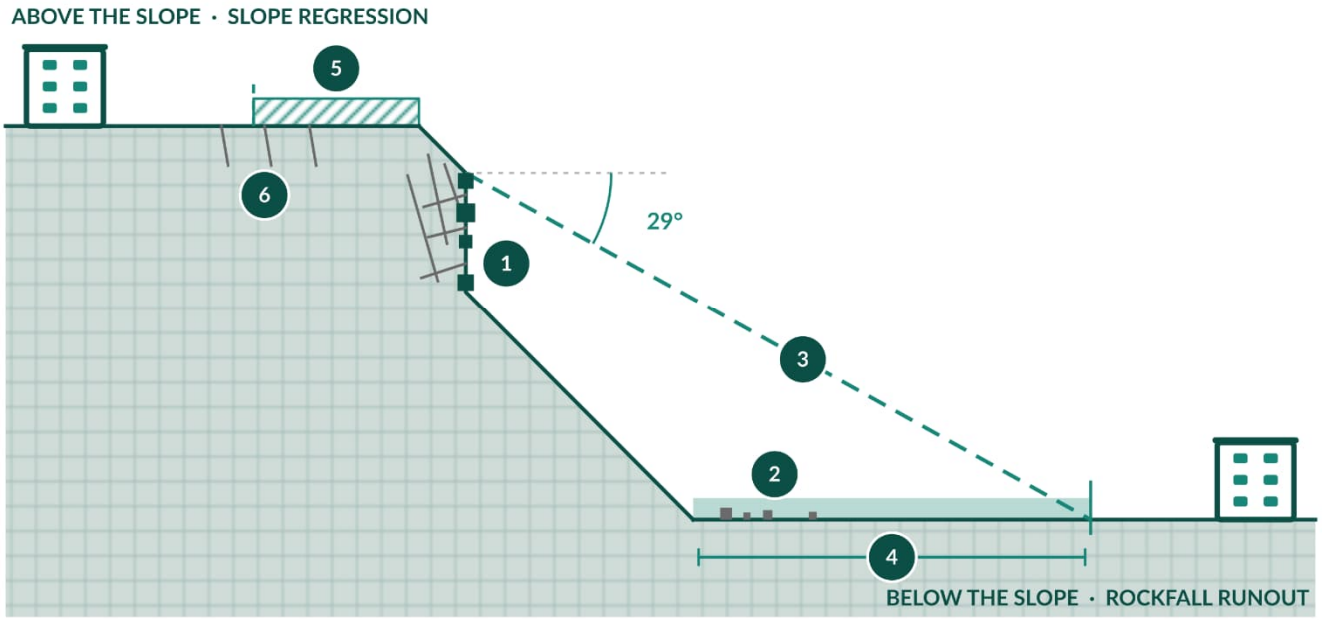
8.2 Assessment methodology

A general approach for assessment of rockfall runout is provided below.

Step 1: Site walkover

Rockfall runout (below the slope). Confirm credible rockfall sources by observing the slope above the site. A credible source is exposed rock that can release: defect-bound or loose rocks, open joints, weathered faces, overhangs and undercut faces, perched rocks, and cut faces / over-steepened slopes. Observe fresh scars, fallen rocks and impact marks. If no credible rockfall sources are identified, then the site is not considered susceptible. Where rockfall sources are present, project a line at 29° from the horizontal (the outer limit of the medium susceptibility runout envelope) from the uppermost credible source to where it meets the ground: development in this area requires further consideration.

Slope regression (above the slope). Walk the mapped zone and look for evidence of slope instability that may extend it further from the crest, such as tension cracks, slumping, karstic features, undercutting of the slope face, and any crest retreat. Where instability is identified beyond the slope regression zone, that land should also be considered potentially unstable.



1 credible rockfall sources: defect-bound or loose rocks, open joints, weathered faces, overhangs and undercut faces, perched rocks, cut faces / over-steepened slopes

2 fresh scars, fallen rocks and impact marks

3 line projected at 29° from the horizontal, the outer limit of the rockfall runout envelope

4 EEETA mapped rockfall runout zone

5 EEETA mapped slope regression zone

6 tension cracks, slumping or other features that might indicate the regression zone extends further.

Figure 8.2 The two susceptible areas at a slope: the 29° projection from the uppermost credible source below the slope, and the mapped regression zone above it.

> WHAT HAPPENS NEXT?
>
> The outcome of the site walkover determines what happens next. Where the walkover confirms the building sits outside the susceptible areas, further assessment is not required. Where the building remains within either area, a site-specific assessment by a geotechnical specialist is strongly recommended before design proceeds.

Step 2: Site-specific assessment

The site-specific assessment replaces the slope susceptibility overlay as the basis for design at the site, as it is based on the actual slope and ground conditions. It may confirm, reduce or extend the susceptible area shown on the overlay map. Where the assessment confirms the site remains susceptible, physical mitigation will generally be required.

A site-specific slope instability assessment can be expected to cover the following (Table 8.1), including confirmation that any selected mitigation option meets the relevant performance requirements.

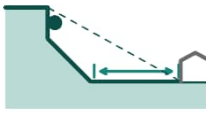
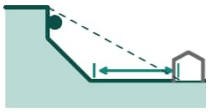
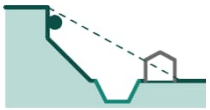
Table 8.1 What a site-specific slope instability assessment can cover

What the specialist does	Rockfall runout (below the slope)	Slope regression (above the slope)
1 Engineering geological mapping	Mapping of the rockfall source area to assess failure mechanism, credible release locations and volumes.	Mapping of the face and crest, including defects, tension cracks, slumping etc to assess failure mechanism and movement to date.
2 Geotechnical investigation and surveys	Block size survey (in-place and fallen rocks), surveyed slope sections to record design block (commonly 95th percentile) and slope geometry.	Investigation including drilling behind the crest to assess profile of ground conditions, weathering, defects, groundwater etc.
3 Analysis and modelling	Rockfall trajectory modelling to assess runout distance, impact energy, bounce heights (usually 95th percentile) where intercepted.	Slope modelling to assess stability of the credible failure mechanisms, seismic performance, tolerable displacement.
4 Consideration of triggering events	Rocks released per design event, for considering appropriate mitigation option and maintenance / inspection requirements.	Expected crest retreat in a design event.
5 The revised susceptible area	Site-specific runout envelope.	Site-specific regression envelope.
6 Consideration of other landslide mechanisms	Whether other mechanisms (for example shallow soil slides, debris avalanches) also affect the site, and any assessment they require.	
7 Design of mitigation options (if necessary)	Analysis of measures selected from Section 8.3 and a design specification, with inspection and maintenance requirements, for the building permit application.	
8 Consideration of residual risk	A record of the residual risk that will remain to structures following mitigation measures.	

8.3 High-level management strategy

The preferred order for mitigation strategies to manage slope hazards is to set back, reduce, protect, stabilise, and accept only where the residual consequence is low. Tables 8.2 and 8.3 provide high-level mitigation options to manage rockfall and slope regression respectively.

Table 8.2 High-level options for managing the rockfall hazard

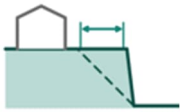
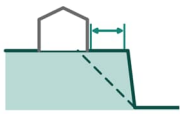
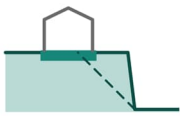
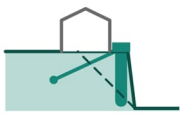
	OPTION	ADVANTAGES	LIMITATIONS	UPFRONT COST
	**Avoid** Keep the building out of the credible runout reach; costs nothing but land.	First option on every site where space allows.	Limits available space for development.	nil
	**Partial setback** Move the footprint as far back as the site allows, with the least sensitive parts of the structure nearest the slope.	Sites that cannot achieve the full distance but can absorb most of it.	Only partially reduces the exposure, so it should be paired with an option below.	nil
	**Scaling or local slope trimming** Removes the most obvious unstable rocks; useful as a supporting measure, not usually the only measure.	Directly addresses the identified rockfall sources rather than intercepting falls. Quick to carry out, and easily combined with the other options.	Weathering keeps loosening new rocks, requiring re-inspections and repeat scaling. Steep faces need rope-access crews.	low
	**Catch ditch** A shaped, soft-floored trap at the toe that stops rocks before they reach the building.	Sites with width to spare at the toe; the cheapest engineered option, ordinary earthworks.	Loses effectiveness once part-full. Needs machine access and regular clean-out.	low
	**Slope modification** Reshaping the slope to a more favourable geometry that reduces runout, e.g. an L-shaped profile or a benched cut.	Reduces the hazard at source; ordinary earthworks plant, and pairs well with a catch ditch at the toe.	Cutting into the face can destabilise the slope, and can affect upslope land and structures.	medium
	**Earth bund** An earth embankment that absorbs block impact by deforming; the highest-capacity option, built from local fill.	Flatter ground (slopes below about 20°) with room for its footprint.	Large footprint and laydown area. Drainage and overland flow paths need design.	medium
	**Rigid barrier** A stiff wall of concrete, gabions or timber (shipping containers have served in New Zealand) that stops lower-energy rocks.	Tight sites with little space behind the barrier, and modest block energies.	Damaged by events larger than it was sized for. Pair with a catch area where possible.	medium
	**Catch fence (flexible barrier)** A tested net-and-post kit, usually imported from a specialist supplier, that stretches to absorb high energies.	Steep, confined or hard-to-access slopes where earthworks are impractical.	Imported kit, specialist design, corrosion in coastal air, and clean-out / repairs after every significant event.	high
	**Attenuator (draped net)** A net tail that slows rock and steers it to a collection point rather than stopping it.	High-frequency sources. Largely self-clearing.	Needs a collection area below, and suits rocks up to about 1.2 m.	high

Costs are indicative relative: nil to high.

NOTES

- Early planning of the site layout to avoid these areas is usually the most cost-effective approach, such as using land within the regression area for low-value uses, such as parking, or non-habited structures.
- The sizing of each engineered option (e.g. catch ditch geometry, bund height, barrier and fence energy ratings, and attenuator layout) depends on the design rock size you are protecting against, impact energy and bounce height from site-specific rockfall trajectory modelling by a geotechnical specialist.
- Options are usually combined: a partial setback paired with one interception measure is the common arrangement, with scaling as a supporting measure.
- Each option has a design capacity, and a larger event can exceed it. The residual risk that remains after mitigation should be recorded and agreed.
- Interception options (e.g. catch ditch or barrier fence) only work while they are maintained. The inspection and clean-out regime should be recorded with the building permit application.

Table 8.3 High-level options for managing the slope regression hazard

	OPTION	ADVANTAGES	LIMITATIONS	UPFRONT COST
	**Avoid** Keep the building behind the regression line.	The preferred response on every crest site.	Confirm the line by crack mapping, not by the overlay edge alone.	nil
	**Partial setback** Move the footprint as far back as the site allows, with the least sensitive parts of the building nearest the edge.	Sites that cannot achieve the full distance.	Reduces the exposure rather than removing it, so it is paired with an option below.	nil
	**Stiff, tied foundation** A reinforced raft, or ground beams tying footings into one rigid platform, so the building moves as a unit rather than breaking up (refer Section 10).	Low-rise, lightly loaded buildings where minor slumping and differential settlement are the credible outcome, rather than complete collapse.	Limits damage rather than stopping movement. Does not prevent the loss of ground from under part of the footprint.	low
	**Row of piles behind the crest** One or more rows of bored piles carried through the potential failure mass into stable limestone, tied together by a capping beam; anchoring (tie-backs) may also be required.	Constrained, high-value developments where the failure surface is deep and ground movement would exceed the structure's performance requirements, i.e. deflection cannot be tolerated.	Likely needing international specialists and a piling rig. The piles limit movement rather than prevent it. Anchoring may be needed to limit deflections further.	high

Costs are indicative relative: nil to high.

NOTES

- Roof water, runoff and drainage should always be directed away from the slope crest and face.
- Early planning of the site layout to avoid these areas is usually the most cost-effective approach, such as using land within the regression area for lower consequence uses, such as parking, landscaping or a light deck on independent foundations.
- For IL1 and IL2 buildings where the likelihood of damage, and the cost and disruption of repair, are acceptable, consider lightweight or recoverable construction, such as a light structure on a tied platform or skids that can be relocated if the line retreats, jacking points for re-levelling, and slack, flexible service connections where they cross the potential failure line.

DETAILED GUIDANCE FOR ASSESSMENT AND DESIGN:

- 1. MBIE / NZGS (2016) Rockfall: design considerations for passive protection structures. The New Zealand design guide for catch areas, bunds, barriers, fences and attenuators, including energy ratings, maintenance regimes and worked examples.
- 2. NZGS Slope Stability Geotechnical Guidance series: Unit 1 General Guidance (2024), and Unit 4 Mitigation and Design Principles. Hazard assessment, runout geometry, and the full mitigation option set for slopes.
- 3. Pierson, Gullixson and Chassie (2001) Rockfall Catchment Area Design Guide (Oregon DOT / FHWA). Design charts for catch area widths below cut slopes.
- 4. de Vilder et al. (2024) Landslide Planning Guidance, GNS Science. The land-use planning framework for landslide risk, written for councils and consenting authorities.

09

9 Fault surface rupture

What this section covers

- Where it applies
- Assessment methodology
- High-level management strategy

9.1 Where it applies

Fault surface rupture is the most localised and uncertain geohazard in the Port Vila CBD. It can damage a site directly through permanent ground displacement, and it applies to sites within the fault deformation overlay.

Permanent ground deformation can occur within these corridors and should be allowed for in design. The EEETA study provided a preliminary screening-level fault displacement estimate of permanent ground displacement across the footprint, of the order of 200 to 400 mm in a single event.

The overlay corridor is taken as the greater of 20 m either side of the mapped or inferred fault, or the corridor extended to the crest of a visible escarpment.

> WHAT THE VNBC REQUIRES
>
> B3.5 Other Geotechnical Hazards (extract)
>
> "Construction Near Active Faults: complex and multi-storey buildings and public buildings of importance factor > 1 shall not be constructed within 20 m perpendicular to an active fault whether known or inferred. Consult the Vanuatu Meteorology and Geohazards Department for fault trace information, mapping, and to obtain necessary development permissions. Advice shall be sought from a suitable qualified geotechnical engineer (*Professional Consultant*)."

> NOTES
>
> Inside the fault deformation overlay, the design objective is no collapse, not continued function. A building designed to that objective is achievable for IL1 and IL2 regular-shaped low-rise construction at reasonable cost, using measures available in Port Vila.
>
> For buildings that are complex, multi-storey, or need to remain functional after an event, which includes IL3 and IL4 buildings, the response is avoidance. Where this is not practical, the approval authority and the Vanuatu Meteorology and Geohazards Department should be consulted (VNBC B3.5), and a geotechnical specialist should be engaged to undertake a detailed site-specific study of the fault deformation hazard.

9.2 Assessment methodology

A general approach for assessment of fault rupture is provided below.

Step 1: Screening

Check the proposed building footprint against the fault deformation overlay maps to establish whether it is affected (within the 'corridor'). Where no part of the building footprint falls within the corridor, no further assessment is recommended.

Where any part of the footprint remains inside the corridor, a site-specific assessment by a geotechnical specialist is strongly recommended before design proceeds. Moving the building out of the corridor removes the hazard.

Step 2: Site-specific assessment

Where a site-specific assessment is undertaken, it replaces the fault deformation overlay as the basis for design at the site, as it is based on site observations and the actual ground conditions. It may confirm, narrow, widen or shift the corridor shown on the overlay map. Where the assessment confirms the site remains within the corridor, avoidance or design to the no-collapse objective will generally be required.

A site-specific study can address where the fault is (with uncertainty expressed), how far the ground is likely to move, and how often it moves. Resolving movement and recurrence will likely require specialist involvement, extensive trenching and palaeoseismic dating which can be very expensive.

Where space to relocate the building is limited, a study focused on locating the fault is often sufficient, without assessing movement and recurrence. Knowing where the fault is may allow the building to be positioned clear of it.

A site-specific fault assessment can be expected to cover the following (Table 9.1).

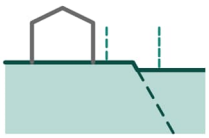
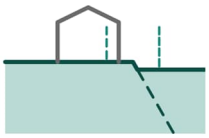
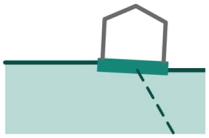
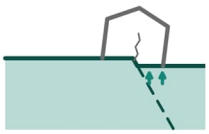
Table 9.1 What a site-specific fault assessment can cover

What the specialist does	What to expect
1 Desk study	Review of the available fault mapping, aerial imagery, earlier investigations and December 2024 ground movement, with geomorphic and geological mapping of the surroundings.
2 Geotechnical investigation to locate the fault	Boreholes and potentially test pits or trenches set out on lines crossing the corridor, to attempt to identify fault offset of a geological unit that is continuous across the site, for example the Efate Pumice Formation, or a specific bed within the limestone. The interpretation relies on a marker that can be traced between holes. This should give a relative sense of movement, and a location or zone where deformation is expected to occur as either a sharp break or spread as warping across a wider area.
3 Palaeoseismic trenching and dating	A trench excavated across the fault and logged by a specialist, with dating of displaced layers, to assess how many times the fault has ruptured, how far the ground moved in each event, and the average time between events (the recurrence interval). This is expensive and requires niche expertise. It is unlikely to be practical for most developments in Port Vila.
4 The revised susceptible area	A site-specific fault setback, replacing the overlay, surveyed so it can be set out on site. The revised corridor may be narrower than the overlay, and it may also be wider or in a different position.
5 Design of the response (if necessary)	Assessment of the measures selected from Section 9.3 and a design specification for the building permit application, covering the foundation and any additional mitigation works.
6 Consideration of residual risk	A record of the risk that will remain to the building after the response is designed, including the possibility of damage beyond economic repair.

9.3 High-level management strategy

The preferred fault response hierarchy in this guidance is adapted from New Zealand guidance, including the Ministry for the Environment (2003) active fault guidelines and the Ministry of Business, Innovation and Employment (MBIE, 2012) Canterbury guidance. Table 9.2 summarises the response options in order of preference.

Table 9.2 High-level options for managing the fault rupture hazard

	OPTION	ADVANTAGES	LIMITATIONS	UPFRONT COST
	**Avoid** Keep the building footprint outside the overlay corridor. The corridor itself provides space for parking, access, landscaping or structures where the likelihood of damage and the cost of disruption and repair are acceptable.	Strongly recommended for IL3 and IL4 where possible, and usually preferred for all buildings where practicable.	Needs room on the site. Uncertainty in the actual fault location, which may lie outside the fault deformation overlay.	nil
	**Partial setback** Move the footprint as far from the mapped fault as the site allows, with the least sensitive parts of the building nearest the corridor.	Constrained sites that cannot clear the corridor but can move the footprint off the centre of the mapped fault.	Likely to reduce the exposure rather than removing it, so it should ideally be paired with an option below.	nil
	**Stiff, tied foundation** A stiff, well-tied shallow foundation, e.g. ground beam grillage, or a stiffened ribbed or waffle raft, spanning the loss of support. Built to be jacked back to level, depending on amount of movement.	May suit IL1 to IL2 low-rise buildings where the displacement is acceptable and the footprint cannot be moved.	A conventional raft is a minimum. Tilt cannot be designed out, and size and height are likely to be limited to maintain structural stability.	low
	**Accept** Keep the building in the overlay, with a recorded understanding that severe damage may occur in a rupture event. Likely not repairable and should be designed to avoid collapse risk.	Only for lower importance buildings, where the residual risk is acceptable to all stakeholders.	The building is likely to be damaged beyond economic repair.	nil

Costs are indicative relative: nil to high.

WHAT THE RESIDUAL RISK RECORD SHOULD STATE

Where a building remains inside the fault deformation overlay, the residual risk record for the project should explain:

- Why the fault could not be avoided.
- The design displacement adopted, its basis, and its uncertainty.
- Which measures were adopted, and the performance they are expected to achieve.
- That the building may be damaged beyond economic repair in a fault rupture event, but is unlikely to collapse.
- That there are considerations to repair the building following a rupture event, such as re-levelling, and how that would be done.

NOTES

- Early planning of the site layout to keep the building clear of the corridor is usually the most cost-effective response. The corridor itself can carry parking, access, landscaping or structures where the likelihood of damage and the cost of disruption and repair are acceptable.
- Options are usually combined. A partial setback paired with a stiff, tied foundation is likely the common arrangement for a low-rise, low importance structure where the corridor cannot be cleared.
- Designing the structure to tolerate the deformation may suit some lower consequence buildings, but it is less likely to be acceptable for essential or high occupancy buildings.
- Services, access, retaining structures and site drainage cross the corridor as well as the building. A structure that survives the movement can still be unusable if its connections are severed, so flexible service connections and a repairable access route may form part of the design considerations.

DETAILED GUIDANCE FOR ASSESSMENT AND DESIGN:

- MBIE (2012, and later amendments) Repairing and rebuilding houses affected by the Canterbury earthquakes, Parts A, B and C.
- Bray, J.D. (2001) Developing mitigation measures for the hazards associated with earthquake surface fault rupture, Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities, Japan Society for the Promotion of Science, University of Tokyo, pp. 55–79.
- Oettle, N.K. and Bray, J.D. (2013) Geotechnical mitigation strategies for earthquake surface fault rupture, Journal of Geotechnical and Geoenvironmental Engineering 139(11), pp. 1864–1874.
- Ministry for the Environment (2003) Planning for development of land on or close to active faults.
- Van Dissen, R.J. and others (2019) Impacts of surface fault rupture on residential structures during the 2016 Mw 7.8 Kaikōura earthquake, Bulletin of the New Zealand Society for Earthquake Engineering 52(1).

10

10 Foundation and ground improvement options for Port Vila

What this section covers

- Foundation concepts
- Ground improvement concepts

10.1 Foundation concepts

This section describes a selection of foundation concepts that are likely to be appropriate for the range of ground conditions found in Port Vila. The foundation solution will depend on the geohazards that apply, project constraints, the building size, complexity and importance level, and what can be constructed reliably in the local market.

In practice, the foundation decision should follow the same sequence used through this guidance: confirm the ground conditions through the investigation, assess the geohazards, then choose the foundation concept that can achieve the required level of performance. Figure 10.1 sets out that choice for the Port Vila ground zones. This guidance does not provide methods for developing geotechnical design parameters or undertaking a detailed foundation design.

> WHAT THE VNBC REQUIRES
>
> BP3 Foundations and Ground Conditions
>
> "Foundations shall be designed, and ground conditions verified to prevent building damage, partial or total building collapse, and unacceptable building movements during its design life; and including current and future conditions/behaviour of the ground and water levels."

Conceptual foundation solutions that are likely to be suitable for Port Vila include:

1. Conventional pad, strip or mat foundation on natural ground. This foundation system is generally suitable for light-to-moderately heavy structures supported on ground with a minimum ultimate bearing capacity of 300 kPa and not underlain by liquefiable soil. These foundation systems may be appropriate for more heavily loaded structures with site-specific assessment and/or ground improvement to improve ultimate bearing capacity.
2. Reinforced raft or well-tied together strip/ground beam on natural or improved ground. This foundation system is generally suitable for light-to-moderately heavy structures underlain by weak or liquefiable soils. The suitability of this system will be dependent on the building's ability to tolerate ground settlement and achieve the required bearing capacity. For buildings with low tolerance for settlement, heavier buildings or sites with very soft/loose soils, additional ground improvement may be required.
3. Bored or driven piles to transfer load to rock/competent stratum. This foundation system is generally suitable for heavily loaded buildings, buildings with low tolerance for settlement or where it is impractical to improve the ground to accommodate shallow foundations.

KEY CONSIDERATIONS WHEN APPLYING THESE FOUNDATION CONCEPTS IN PORT VILA:

- Foundations should be selected and designed with the project structural engineer to resist vertical, horizontal and overturning actions under static and seismic loading.
- Port Vila CBD buildings are predominantly: lightweight low-rise residential; low-rise concrete framed with masonry infill; and larger, heavier buildings of higher importance level.
- The concepts and process in this guidance predominantly apply to one to three storey concrete framed structures.
- Lightweight low-rise residential buildings are generally able to tolerate ground settlement and be repairable after an earthquake. Reinforced raft or well-tied foundations provide increased resilience in liquefaction-prone areas and can be considered for these structures.
- Larger structures generally require a specific design. The concepts presented in this guidance may provide a useful starting point at concept stage.
- Zone A and B sites, typically within 200 m of the coast, may be prone to lateral spread. For one to three storey concrete framed buildings, reinforced raft or well-tied foundations are recommended to resist lateral stretch. Larger, higher importance structures may need more robust measures such as perimeter treatment to mitigate lateral spread hazard and/or piles that extend through the liquefiable soils and are designed to resist lateral soil loads.
- Excavations, particularly below the groundwater level or close to neighbouring buildings, need careful planning, an engineering assessment of temporary and permanent support, and verification of the ground conditions during construction.

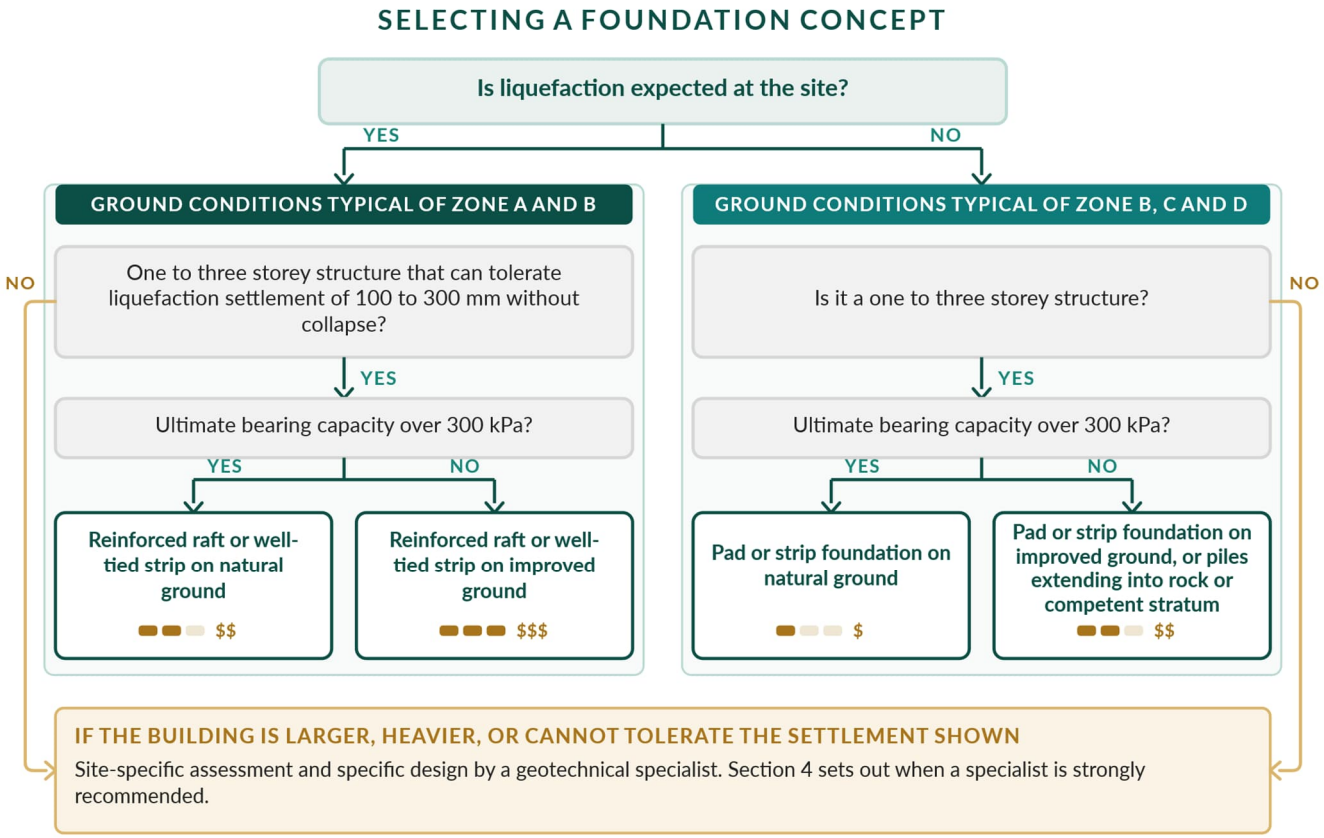


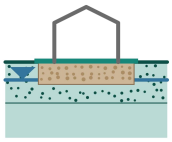
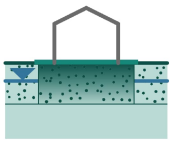
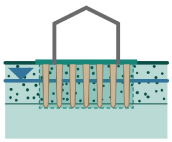
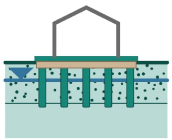
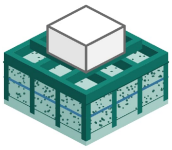
Figure 10.1 Selecting a foundation concept for the Port Vila ground zones.

10.2 Ground improvement concepts

This section presents broad level ground improvement options that are generally considered suitable for ground conditions encountered in Port Vila. Ground improvement options generally fall into the categories below. Table 10.1 compares them in order of increasing cost and robustness.

- Treatment of shallow soils through replacement (such as gravel raft with or without geogrid reinforcement) or densification (such as dynamic compaction). The methods are suitable for improving bearing capacity and to reduce liquefaction-induced differential settlement. May not treat the full thickness of liquefiable soil, with reduced effectiveness for sites with significant lateral spread hazard.
- Construction of rigid inclusions (such as driven timber piles or bored concrete piles) to create a composite block of improved soil. Can be used to distribute load to a more competent stratum or reduce the potential effects of liquefaction within the improved block.
- Mass soil stabilisation (such as soil mixing) or reinforcement (such as lattice grids). Typically the most robust ground improvement option in lateral spread areas, but costly and requires specialist plant and expertise.

Table 10.1 Ground improvement techniques suited to Port Vila, with their advantages, limitations and relative cost

	OPTION	ADVANTAGES	LIMITATIONS	UPFRONT COST
	**Gravel raft** Replace 1 to 3 m of soil with compacted dense gravel to reduce differential settlement.	Conventional construction equipment. High confidence in level of treatment.	Shoring/dewatering required when excavation extends below groundwater table. May not be effective for areas with significant lateral spread effects.	low
	**Dynamic compaction** Compact soils by repeatedly dropping a 5 to 20 t tamper from a crane in 2 to 6 m grids.	Fast and economic, and can typically be undertaken using conventional equipment. Easy to verify improvement.	High vibration and noise; requires clearance for crane. Needs post-improvement testing to verify.	low
	**Driven timber piles** Drive timber piles in a 1.2 m to 1.6 m grid to create a composite block.	Secondary benefit of densification in addition to creation of a composite block.	Heaving of ground near the improvement piles. Adverse vibration and ground deformation for neighbouring structures.	medium
	**Rigid inclusions** Construction of stiff columns (such as augered concrete piles) at 1.5 m to 2.5 m grids.	Less vibration. Increases bearing capacity of weak soils.	May require specialist plant and machinery not readily available in Port Vila.	medium–high
	**Lattice** Grids of intersecting walls with 5 m to 7 m grid spacing.	Effective in areas with lateral spread. Likely the most robust ground improvement to reduce effects of liquefaction.	May require specialist plant and machinery not readily available in Port Vila.	high

PUBLISHED LITERATURE WITH COMPREHENSIVE DESIGN METHODS FOR FOUNDATION DESIGN:

- Foundation Analysis and Design by Joseph E. Bowles (1997)
- Foundation Design and Construction by Michael J. Tomlinson and R. Boorman (2001)
- The Engineering of Foundations by Rodrigo Salgado (2007)
- Federal Highway Administration – Ground Modification Methods Volume I and II (2017)

NEW ZEALAND SPECIFIC GUIDANCE THAT MAY BE USEFUL:

- Earthquake Geotechnical Engineering Practice Module 4: Earthquake resistant foundation design (2021)
- Earthquake Geotechnical Engineering Practice Module 5: Ground improvement of soils prone to liquefaction (2021)
- Canterbury Technical Guidelines Part A to D (2012)