The Scott Base redevelopment: design response to natural hazards

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ABSTRACT

The Antarctic environment is extreme, making consideration of resilience crucial for survival. This paper outlines how site-specific hazards are being considered within a resilient design framework for the Scott Base Redevelopment project.

Scott Base is located at Pram Point on Ross Island in the Ross Sea. The base is 30 m from the sea edge, 16 m above mean sea level and 38 km from an active volcanic lava lake at Mount Erebus. Antarctica is the most remote, coldest, windiest and driest continent on Earth, and subject to natural hazards, so a systematic and robust approach to consideration of the hazards is crucial to ensure the building can sustain life.

Site specific consideration of wind and temperature (NIWA), seismic, volcanic eruption and tsunami (GNS Science) risks have all been undertaken to inform the design of the new base. This paper outlines how these studies have been used to adopt design criteria which consider a consistent and acceptable level of risk and resilience. Understanding of these risks and how they are applied to design in the context of the New Zealand Building Code, and the impact on the Base design are explored.

1 INTRODUCTION AND CONTEXT

The Scott Base Redevelopment project consists of a completely new base in New Zealand's claim to Antarctica, the Ross Dependency. The new base will replace the existing, ageing base and has a design life of 50 years, maintaining a presence and facilitating scientific study on the least known and most extreme continent. The project is currently within the Developed Design Stage.

Scott Base lies on Pram Point on Ross Island, bordering the Ross ice shelf. The site directly borders the Ross Sea, and is surrounded by sea ice, which occasionally breaks out during the summer months. The continuously active volcano, Mt Erebus dominates the landscape behind the base. Due to the unique geology and southern latitude (77.8° S) it is susceptible to many Natural Hazards. Access is by annual supply ship or by air flying the 3,823km from Christchurch. Due to the remote location of the base, extreme weather, and natural hazards, a high level of resilience is required to ensure the safety of staff and ongoing operation of the base is maintained. As a result of the latitude affecting daylight seasonally, work can only be performed outdoors for the 4 months of the summer season. Further specific details of the geological natural hazards can be found within and presented in the accompanied paper (Burbidge, et al., 2020).

1.1 Extreme environment considerations

The temperatures at Scott Base vary from just above freezing at the height of summer to annual lows of -48°C in July providing challenging considerations for material selection. The lowest recoded temperature at Scott Base is -57°C. In addition, the cold, dense air has extremely low humidity (0.7g/kg of air), resulting in dry, spindrift snow, and causing shrinkage issues with material such as timber which is normally considered "dry." At a density of 1.4kN/m3, the air is 17% more dense than assumed in the New Zealand Loadings Code (Bull, 1971). Ross Island is within the southern continuous permafrost zone, with an active layer identified as between 0.1 and 0.9m, proving challenges for designing resilient foundations including considerations of any changes overtime of the active layer due to climate effects which could change over time (Intergovernmental Panel on Climate Change, 2013).

Wind speeds in the Ross Island region are very high, which requires special considerations for the structural design. Wind also generates snow drifting, which is problematic for maintenance.

The risk of distant or near source tsunami events is present at the base, and effects base siting, and ancillary site structures (Burbidge, et al., 2020). Additionally, the risk of ashfall from a volcanic eruption from Mt Erebus could influence the continuity of operation of air handling plant and hence is an important resilience consideration for the base.

Related to the volcanic eruption risk there is a seismic risk to the base which could change with significant climate effects, such as isostatic rebound, where the reduction in ice weight on land causes localised tectonic uplift (Burbidge, et al., 2020), (Henry, 2008). While low compared with wind it does have influence on non-structural components and diaphragm design.

1.2 Compliance

As it is within New Zealand's jurisdiction, compliance is with the New Zealand Building Act and other relevant legislation. Where necessary, additional technical requirements are to international best practice.

There is no suitable local New Zealand precedent for design in this environment. While there have been a number of other bases built throughout Antarctica, of varying size and complexity, Scott Base provides a number of unique challenges. The founding on an active permafrost layer, not present in more southern bases, the site-specific hazards, extreme environment and logistics challenges provide require a resilient design approach to be taken.

2 PROCESS CONSIDERATIONS

With a number of unique requirements and conditions to address in the design, some order is needed to manage design decision making to achieve a resilient design that crosses disciplines effectively. Current practice in New Zealand for decision making within a building project and specifically the design stages, has progressed to include processes each aimed at addressing a key aspect critical to delivering a building project. These include maintaining a risk register for the project and following a Health and Safety by Design process. Other processes are followed to demonstrate quality assurance and optional aspects such as Green Star and Soft Landings.

Recently “low-damage” seismic design has been a term used to promote structural systems that provide enhanced performance over other, conventional systems. Low-damage is a subjective term, however and it is difficult for the industry to provide consistent interpretation of this to a public audience. In a similar way, the term “innovation” is also prone to being used out of context when applied to design and can result in unjustified complexity of design.

Resilience is perhaps a better term to use in building design, as it not only elevates good structure design, but includes other components that make up the whole. A truly resilient building must be resilient as an integrated sum of the parts, not one component or system considered in isolation. Resilience is also a term that resonates with a wider group as it is a term used across sectors and industries.

Resilience can be defined as, “the ability of an asset or community to withstand or recover in a timely manner from the effects of a significant disruptive event”. Globally a number of organisations such as the US Resiliency Council have been formed recognising the importance of whole-building resilience. This is driven by the public expectation for better buildings that adequately consider a range of possible events during their life and continue to be of service providing reliability, flexibility of use and value for money. For these reasons and as insurance is becoming increasingly costly, resilient buildings are becoming more important to long-term building owners, and communities.

Design for resilience is focussed around a possible disruptive event that could occur and considering the preparation in terms of design that can address the likelihood and/or consequence of that event. When this is omitted or poorly considered, a more significant response and a long and costly recovery can be expected (Figure 2).

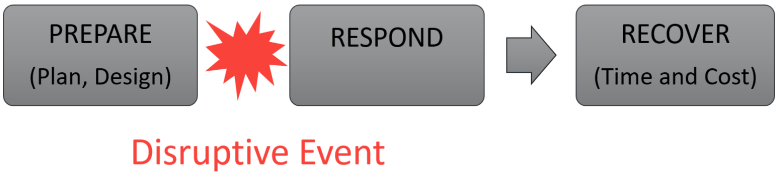


Figure 1 - Activities related to a disruptive event

2.1 Approach to Resilience

A proposed approach considering resilient design is illustrated in Figure 3 for the Scott Base Redevelopment. This qualitative process is a way of carrying out good design that can be linked back to the project requirements and objectives in a systematic way. In some ways this can be considered similar to Safety by Design approach (and can be integrated with Safety by Design), but it is intended to be more comprehensive - focussed on how the design solution addresses the project needs directly rather than relying on an agreed collation of project risks and mitigations.

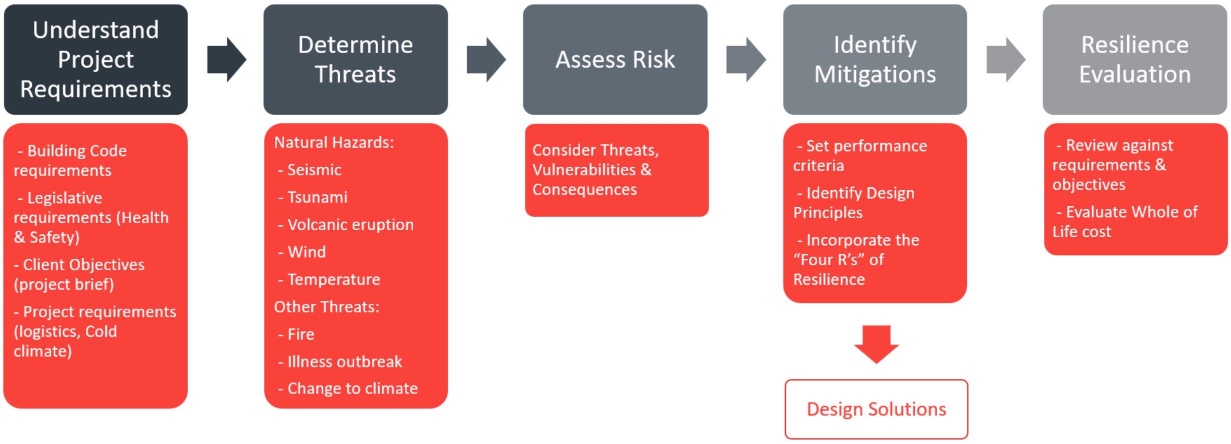


Figure 2 - Proposed resilience evaluation process

2.2 Basis of Risk Evaluation

From understanding the project requirements and hazards, specific threats can be identified, and the hazard understood. This allows the design performance criteria to be set to inform the design and enable an appropriate solution to be provided. To demonstrate how specific design choices addressed the key performance requirements, a multicriteria analysis approach was used. These aspects have been captured in the Design Features Report, and in the Safety by Design Register by the design team. Within the design team a resiliency matrix was used to rationalise building services redundancy.

3 HAZARDS & SOURCES OF INFORMATION

Throughout the early stages of design, hazards that had the possibility of influencing operation of the base were identified, and following this information was sought on a case by case basis for each hazard. For a number of the natural hazards including, tsunami, volcanic eruption and seismic little information was able to be initially retrieved and further studies have been commissioned.

3.1 Wind

NIWA has been monitoring wind speeds at Scott Base since its inception, and as such over 50 years of data has been collected. This data has been used to develop site specific wind speeds for various return periods, to inform the base design. The site is susceptible to maximum wind gusts of 63.1 and 70.5 m/s for the 500- and 2500-year return period events respectively. Figure 1and Table 1 show the wind rose and maximum wind gusts for given recurrence intervals respectively.

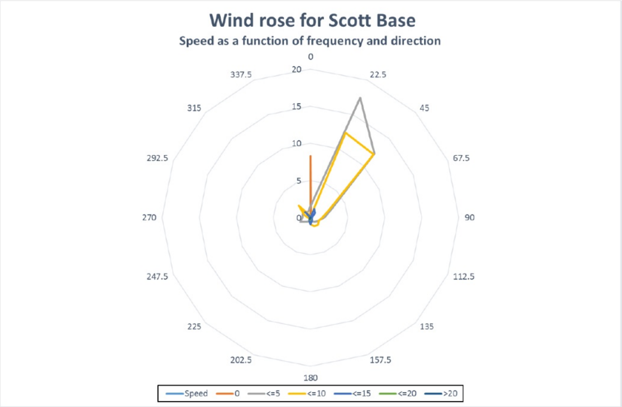


Figure 3 - Wind rose for Scott Base as a function of frequency and direction

Table 1 - Design maximum wind gusts for given recurrence intervals

Recurrence interval (yrs.)	**25**	**100**	**500 (DCLS/SLS2)**	**1,000**	**2,500 (ULS)**
Maximum wind gust (ms^{-1})	49.3	55.7	63.1	66.3	70.5

3.2 Seismic

Based on comparison of similar regions around the globe, Ross Island has been identified to have relatively low seismicity (Z=0.1) (Golder Associates, 2016). A site-specific seismic hazard analysis is currently being commissioned to better understand the potential for damaging seismic events.

3.3 Tsunami

GNS was commissioned to undertake a pilot study of the Tsunami risk to Scott Base to inform the siting of the base above mean sea level. Because of this analysis it was found that the base is most susceptible to a distant-source Tsunami originating from a seismic event in the Mexico region (Burbidge, et al., 2020). The interaction with the wave action and sea ice was also investigated.

3.4 Volcanic eruption

Erebus has been the subject of some scientific research, but there has been little focus on the likelihood of Erebus erupting and what impact that could have. GNS provided comment as to the consequences of such an eruption on Scott Base, which identified that possibility of an eruption could not be ruled out and identified wind-blown ash as a design consideration. Some previous studies have modelled extent of windblown ash for an eruption scenario (Asher, 2014).

3.5 Climate and Temperature

The extreme cold climate affects all aspects of design from material selection and foundation performance to constructability and operation in Antarctica. Historical temperature data has been collated by NIWA, additionally thermistors have been placed in the ground to monitor ground temperatures with depth. Refer Table 2 for design minimum temperatures.

Table 2 - Design minimum temperatures for given recurrence intervals (NIWA, 2017).

Recurrence interval (yrs.)	**1**	**10**	**50**	**100**	**500**	**1000**	**2500**
T_{min} (°C)	-48.3	-54.8	-59.4	-61.4	-66.0	-68.0	-70.6

3.6 Understanding of risk

Much of the hazard information to date has focused on consequence. For example, the determination of likelihood of tsunami and volcanic hazards are difficult to determine without rigorous studies. In order to evaluate the risk fully, both the likelihood and consequences need to be well understood. Where there is an understanding of the consequences, but less certainty regarding the likelihood of an event, careful consideration of the consequences is required in the design.

4 KEY DESIGN PRINCIPLES

4.1 Resilience and Robustness

Resilience in design is incorporated as a minimum requirement as a part of Building Code Requirements – the building has been designated as Importance Level 4 (IL4) due to its high consequences of any failure, and hence inherently resilience is built in through the Serviceability Limit State 2 (SLS2) seismic requirements. In addition to code minimum requirements, a Damage Control Limit State (DCLS) for wind has been introduced, to ensure the base remains operational in significant wind events expected more than once within the life of the building.

4.2 Future Flexibility

Future flexibility is necessary to allow the use of spaces to change without requiring structural changes to be made, or having the structure unreasonably limit what changes in use are made over the life of the building. This includes providing open spaces and pushing the structure to the perimeter of the building where possible and allowing for floor live loads and building services that facilitate a range of possible uses.

4.3 Modular, Repeatable Design

Modular design draws upon the concept of regular repeatable structure and prefabrication which reduces time on site, which is critical for construction in Antarctica. The modular design approach is directly linked to the logistics strategy.

The building envelope, structural frame and floors of the base are proposed to be pre-fabricated in kitset form, so that buildings can be assembled quickly and efficiently. For example, pre-cast composite concrete and steel or timber cassettes are proposed for the floor systems, with grouted connections. Where possible rooms are proposed to be prefabricated as pods, within the building envelope on the structural floor.

It is important to recognise that the extent of modularisation needs to be balanced against the requirement for future flexibility i.e. the ability to reconfigure the space in the future.

4.4 Cold Climate Design

The extreme cold climate affects materials and foundation design in Antarctica. Using appropriate materials and designing for cold temperatures within the life of the structure forms a unique and critical part of the design. The building foundations are in permafrost, and the resulting potential for differential thaw related settlement is one of the key risks to the structural design. The design is targeted to a practical, resilient solution that is appropriate for the conditions in which it is to operate and be built.

Brittle fracture of steel at low temperatures is a design consideration which impacts specification, load demands, construction methodology and the cladding design. Dimensional changes due to temperature are also part of the tolerance considerations. Any timber must consider shrinkage effects.

Ease of operations and maintenance also needs to be addressed, the problem of snow drifting and different building heights is currently a problem at the existing base. This criteria has impacts on the building height, which flows on to effecting snow and wind performance.

5 DESIGN PERFORMANCE CRITERIA

Following the risk analysis, building performance criteria can be set. While the New Zealand Building Code sets minimum limits for building performance, these limits may not necessarily meet the design criteria and client objectives for the base. Therefore, the building performance criteria must be set keeping in mind the risk evaluation and consequences of failure as well as the intended 50 year design life.

A key example of this is the performance of the structure during wind events. For an Importance Level 4 (IL4) structure, NZS 1170.5 required design for a Serviceability Limit State 2 (SLS2) level earthquake. This criterion ensures that post disaster functionality is maintained. There is no equitable limit state for wind events within the New Zealand loading codes. As previously discussed wind speeds at the site are high, and as such are the dominant lateral load with Ultimate Limit State (ULS) wind. There is potential for damage to the structure permitting which could affect the operation of the base in a wind storm expected to occur several times during the life of the base, and as such an intermediate limit state has been adopted for the design. This is termed the Damage Control Limit State (DCLS) which is a term becoming more commonly used in seismic engineering to provide an additional level of damage prevention when the consequence of damage may be higher than a normal building.

Table 3 shows the adopted return periods for the base for the considered design actions. The DCLS return period wind event has been selected as the 1 in 500-year wind speed. The corresponding displacement limits are beyond SLS displacement guidance set by New Zealand loading standards, and as agreed with the façade designer based on accepting some damage such as wall lining cracking, but still ensuring the building envelope is not compromised, and the building remains operational. – these are set based on displacements where damage which affects operations but may be beyond structural deformation which may result in minor damage but does not compromise the building envelope or use of the building. In such an extreme climate, maintaining the building envelope integrity and services operation is key to life safety.

Table 3 - Design Return Periods for Snow, Seismic and Wind Loads.

Importance Level	**Earthquake/Wind Event – Return Period (probability of exceedance in 50-year life)**				
	ULS		**SLS**	**SLS2**	**DCLS**
	(Seismic & Wind)	**(Snow)**		**(Seismic only)**	**(Wind only)**
2	1/500 (10%)	1/50 (63%)	1/25 (86%)	-	-
3	1/1000 (5%)	1/250 (20%)	1/25 (86%)	-	-
4	**1/2500 (2%)**	**1/500 (10%)**	**1/25 (86%)**	**1/500 (10%)**	**1/500 (10%)**

Careful foundation design and selection is required due to the permafrost underlying the site. The variable volcanic soil comprising scoria and basalt with some ice inclusions has an active permafrost layer, which thaws during the summer and re-freezes in the cooler periods of the year. This active layer of permafrost presents unique settlement issues that need to be addressed. The founding depth has been set below this freeze-thaw layer allowing for potential climate change impacts influencing the permafrost over the design life of the base.

6 DESIGN OPTION ANALYSIS

6.1 Site

The site of the existing base at Pram Point occupies the preferable area for development. The site slopes from the hills of Arrival Heights above down the sea, as shown in the site plan in Figure 4.

Figure 4 – Aerial image with 3-D render of proposed developed base.

The current base has been built in stages over an extended period of time. There are 7 main buildings all linked by internal covered walkways across 11 different floor levels. To address this, the proposed base has 4 buildings, each serving different functions stepped down the slope; three of which are two storey buildings and are linked across a total of three levels by elevated bridge structures. The fourth is the hangar building which is separate to the main base.

The separation of the base into four buildings has foundations in both operations and resilience. The buildings are separated based on their hours of operation and noise, floor use criteria, redundancy of essential building services, and it also means the building form is a module of manageable size so each building has the flexibility to be extended in the future. The linkways between buildings provides safe, all-weather access.

There is an immense number of design and operations requirements and constraints which affect the siting, orientation and interrelations between buildings and facilities on the site. The main drivers of the chosen site position are detailed in Table 4.

Table 4 - Factors influencing the site location

FACTOR	**DESCRIPTION**
ENVIRONMENTAL	• The existing site has been used as a base already, hence biodiversity already altered. Expansion of the site should be limited.
TOPOGRAPHY	• Existing buildings are currently positioned on the flattest part of the site.
EXISTING INFRASTRUCTURE	• The Transition Road which provides access from McMurdo Station to the ice shelf passes nearby with a sharp hairpin bend, this restricts expansion of the site. • The power cable from the windfarm/Grid runs overland and a fuel line from McMurdo is expected to do the same in the future.
SCIENCE	• Marine lab needs to be close to the sea to maintain the sea temperature. • Long term science equipment to the west of the existing buildings which has been recording since 1957.

CIVIL	• Access to the sea for water intake and wastewater outfall structures and pipe routes needs to be integrated with other operations.
HEALTH AND SAFETY	• Snow is a hinderance and a help; sufficient for skidoos to access close to buildings is useful but drifting and clearance is a maintenance hassle and can be a H&S risk. • Access for vehicles for visitors, maintenance and science expeditions needs to be on a safe slope with pedestrian and vehicle routes deconflicted.
OPERATIONS	• The helicopters need to be close to the science staging areas but not too close to be a noise problem. • The helicopters need to take off into the wind (prevailing northerly) but not fly over buildings. • If the helicopters are taking off into a southerly they cannot overfly the seals which frequent an area south of the Base.

Following a multi-criteria review, the decision has been made to use the existing site with the buildings positioned further to the north west to improve:

- Separation from the Transition Road.
- Ability to start construction while continuing to use existing buildings.
- Sufficient distance from the shore to protect against Tsunami, wave action and erosion.

6.2 Wind and Snow Engineering

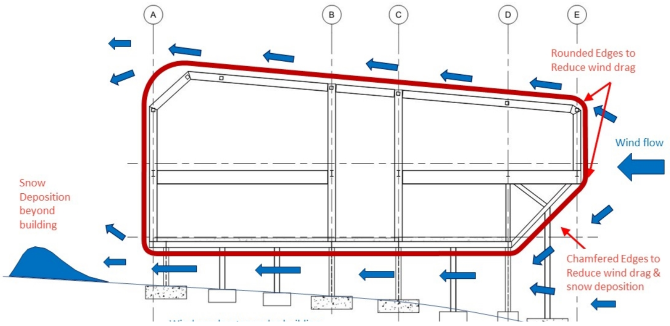


Figure 5 - Building cross section showing wind flow and snow deposition.

The four buildings have been orientated perpendicular to the south wind which is the direction in which the strongest winds originate, and which also brings airborne snow. This allows for an efficient aerodynamic structure, which reduces wind drag and snow drifting. The buildings have been raised off the ground and sufficiently separated so that snow is not deposited between them. The buildings area also most shaped on the southern elevation to reduce drag and accelerate the wind underneath the building to prevent snow deposition underneath. Wind tunnel and snow modelling is being undertaken to verify the performance of the proposed structures and is discussed in Section 7.

6.3 Volcanic Risk

The risk of ashfall from the 30 km distant Mt Erebus cannot be managed by adjusting the base siting, as the risk affects the whole of Pram Point. As such this risk has to be mitigated by the design solutions chosen. From information available and subsequent advice from GNS the likelihood of an eruption is low based on past behaviour, but this could change. In an eruption event it is possible that ash could reach the base in strong winds.

Ashfall is not expected to affect the structural design, however is an important consideration for the heating and ventilation system. Since the consequence of failure of the heating and ventilation system is critical to both life safety and operational continuity, the risk of ashfall needs to be fully understood.

The approach adopted is to mitigate the effects of ash fall by designing the air handling plant and operating procedures to be able to handle the expected type and quantity of ash, via appropriate filters, which includes plans for cleaning and replacement parts.

6.4 Seismic Performance

While seismic loads have a limited impact on the lateral design of the superstructure, they are a key consideration for the design of non-structural element restraint, as well as in-plane racking deformations for cladding – of which both factors affect life safety and operational continuity considerations.

As previously identified seismic hazard is not well understood in the Ross Sea region of Antarctica, hence additional information in the form of the site-specific hazard assessment is being sought.

6.5 Temperature Considerations

Due to the extreme cold temperatures experienced at the site, careful consideration of material selection is required as well as the use of stress limits for temperature to avoid embrittlement. Key considerations include:

- Construction staging – Will the erected steel frame be exposed to the elements over winter before being enclosed?
- Will a change in the climate lead to different weather patterns? This could affect foundation depth, snow deposition, and ice break out and storms affecting the marine structures.

The effect of steel exposed over the winter months can be managed by combining the applicable wind event with the limiting stress for steel in cold temperatures as a design load case. Material composition is of paramount importance to avoid brittle fracture at low temperatures (Hobbacher et al, Eranti). Although no structure yielding is expected, high ductility structural steel (grade SO) is proposed generally to minimise susceptibility to low temperatures, and LO or L15 grades are used where necessary, such as for hollow sections. Alloy fasteners such as 24CrMo4/4130 or 42CrMo4/4140 (BS EN 10269:2013/ ASTM A320) or stainless-steel fasteners (ASTM A2-304 or A4-316) are to be used depending on service application.

Care needs to be taken with quality assurance for structural materials typically using with Charpy V-notch testing to demonstrate compliance or assessing Rockwell hardness. Bolting of critical connections is preferred, as weld imperfections permitted under normal circumstances can lead to brittle fracture. Welding consumables require a Ships' Classification Societies Grade 5 approval. In addition to specification and quality assurance, understanding the construction methodology is important at the design stage. For example, it is proposed that the envelope is completed and the building heated over one summer season, so structural members will not be highly loaded at low temperatures.

6.6 Foundation Design

Embedment of the foundations need to be below the active freeze-thaw layer of the permafrost to prevent any thaw related settlement of the foundations. This embedment depth needs to consider any potential changes in climate which may lead to an increase in the freeze-thaw layer. Thermistor probes have been monitoring ground temperatures in the recent years. This data has been used to determine the proposed founding depth and is displayed in Figure 6.

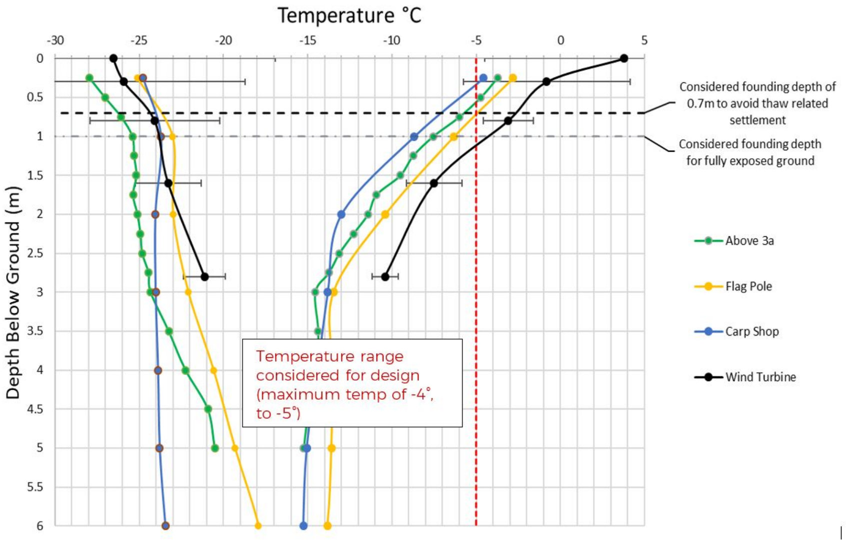


Figure 6 - Thermistor data showing maximum and minimum temperature readings with depth throughout the site.

Two solutions are currently being considered for the foundation design:

- Precast concrete pads with tension anchors
- Ad-Freeze Steel Piles

Precast concrete pads are simple to construct and have been used for the existing Scott Base Buildings. However, they require additional earthworks to piles, and are susceptible to local inconsistencies in ground conditions and thaw related settlement.

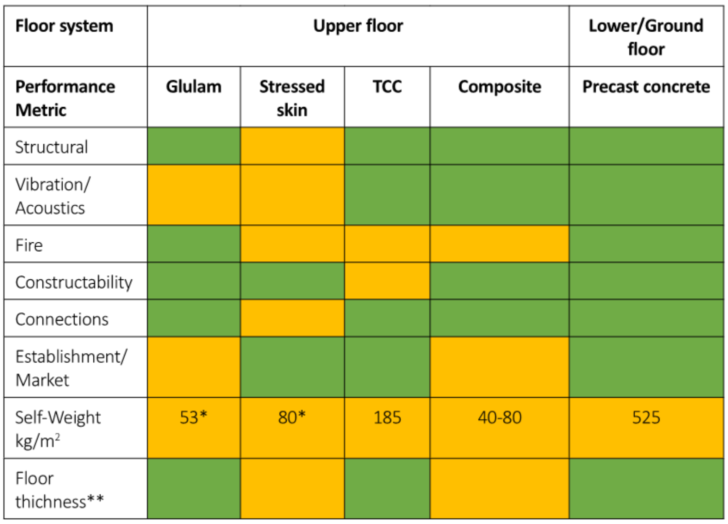
Ad-Freeze piles are not typically used in Antarctica, however are common practise in the Arctic. In this case a modified solution relying on end bearing and locked in place by ice is being considered. This method will also permit the removal of the pile at the end of its life by heating the steel pile. The final solution will be confirmed once geotechnical review and the multi-criteria evaluation of the two options has been completed.

7 EVALUATION

7.1 Multicriteria analysis

Evaluation of design decisions against the design objectives and performance criteria has been carried out using a simple RAG (Red, Amber, Green) analysis, and where weighting is needed, using a multi-criteria analysis. This has helped demonstrate decisions adequately consider the required criteria and provide the resilience required. Refer to Table 5 for an example RAG analysis for the floor systems. Note, TCC refers to timber-concrete-composite, and composite refers to a composite sandwich panel.

Table 5 - RAG analysis undertaken to determine floor systems for the structure.



Floor system	**Upper floor**				**Lower/Ground floor**
Performance Metric	**Glulam**	**Stressed skin**	**TCC**	**Composite**	**Precast concrete**
Structural	🟩	🟨	🟩	🟩	🟩
Vibration/ Acoustics	🟨	🟨	🟩	🟩	🟩
Fire	🟩	🟨	🟨	🟨	🟩
Constructability	🟩	🟩	🟨	🟩	🟩
Connections	🟩	🟨	🟩	🟩	🟩
Establishment/ Market	🟨	🟩	🟩	🟨	🟩
Self-Weight kg/m^2	🟨 53*	🟨 80*	🟨 185	🟨 40-80	🟨 525
Floor thichness**	🟩	🟨	🟩	🟨	🟩

** Weights exclude acoustic & fire proofing*

*** Floor thickness considered in terms of impact on space for building services*

7.2 Testing

Testing and quality assurance forms an important part of resilient design also. Snow modelling has been carried out to demonstrate the building performance and this has resulted in some optimisation of the building shape and confirming clearance to ground. Wind tunnel testing is to be carried out to confirm cladding pressures and the effect of air inlet penetrations, dynamic effects on the link-bridges, and to validate the drag efficiencies on the envelope expected from the profiled building geometry. Drag reduction of up to 40% can be achieved largely by rounding the leading edges of the building profile in the direction of the strongest wind (Rodrigo, van Beeck, & Buchlin, 2012).

8 CONCLUSION

The Scott Base project requires a number of natural hazards be adequately accounted for in the design to provide a resilient building that meets expectations. A qualitative process was identified to assist in linking the project requirements and hazard evaluation to performance criteria and design solutions. These hazards were identified, and site-specific information was gathered or commissioned to understand the risk and set suitable performance criteria. Where necessary, and to illustrate decision making, RAG analysis and weighted, multi-criteria analysis was used. This information has been incorporated in the Design Features Report and the Safety by Design Register in coordination with the project design team. Validation by testing forms an important part of delivering a resilient design for this project.

Where multiple considerations need to be incorporated in design, this approach is useful to navigate multiple choices and design options. This also demonstrates how a resilient design approach can be integrated into building design and linked into existing processes such as Safety by Design.

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