Foundation Remediation at Sandy Cove, St. James, Barbados

Sandy Cove Condominium development on coralline rockmass

The west coast of Barbados is home to platinum white beaches, the sparkling Caribbean Sea, the rich and famous, and some extremely challenging foundation conditions. The island largely comprises coralline limestone formed in terraces up to 260 ft (80 m) thick; the remains of ancient coral reefs. While technically rock, this coralline limestone has strength so low in many places that its properties approach that of a hard soil. The coralline rockmass behaviour as a foundation stratum is further complicated by the presence of relict rock fabric, incipient fracturing, numerous voids, fissures and joints. The rockmass, however, can contain an indurated or hardened cap present in various areas including along shorelines in the crest zones of cliffs.

In 2005, construction started on the Sandy Cove development on the west coast of the island. The project included a six-storey luxury condominium complex, with a one-level basement (on the northern half of the building only) and five levels of above-ground units. The building is set-back approximately 50 to 65 ft (15 to 20 m) from the edge of a 10 to 15 ft (3 to 5 m) high coral cliff bordering the Caribbean Sea to the west. An approximately 12 ft (4 m) deep gully/drainage channel is immediately adjacent to the building's north side. The structure, comprised of reinforced concrete and concrete block-wall, was designed to be supported on shallow strip footings on engineered fill or directly on the coralline limestone rockmass.

During the initial site grading and excavation for the basement and foundations, the contractor encountered several small caverns, voids, fractures and zones of very loose material at the footing level in the coralline foundation stratum. These areas were addressed by several methods, including localized sub-excavation and replacement with engineered fill, backfilling of open voids from surface with high slump concrete and by installing six 22 ft (6.7 m) long, 1.5 ft (0.45 m) diameter, augered piles at one location. In addition, the designers modified the foundation design on the northern half of the building in the basement area from strip footings to a reinforced mat/raft about 1 ft (0.30 m) thick, but locally thickened up to 2 ft (0.55 m) at load bearing wall/column locations. The contractor completed the foundations, building structure and exterior shell in April 2006. Between April and August, the building performed as designed while interior and exterior finishes were progressing. However, in August 2006, following several days of heavy seas, cracking appeared on several walls in the northwest corner of the building, near the intersection of the ocean-side cliff face (to the west) and drainage gully (to the north). These cracks initially showed little further

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change and were subsequently patched and interior finishing continued. The design team noted no new cracking or other signs of building movement until early February 2007 when again, following violent sea conditions, the original cracks re-opened and more cracks appeared.

Investigation Assessment

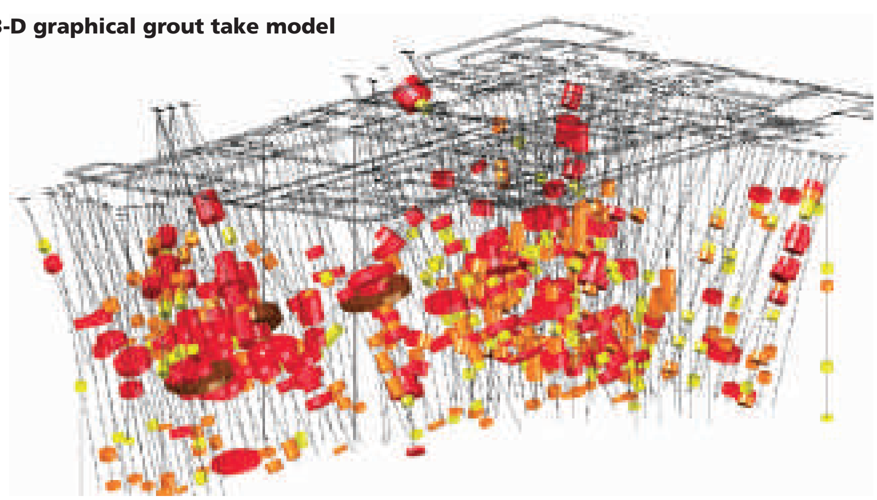
The owner contracted Golder Associates Ltd. in February 2007 to evaluate the foundation conditions, the cause(s) of cracking, and to propose remedial solutions. Golder's investigation included several boreholes from within and beside the existing building with downhole video camera survey, geologic surface mapping of the exposed coral features around the site, and detailed crack surveys. Golder also initiated structure monitoring equipment including crack gauges and precise levelling points.

half of the building. Mapping the coral cliff faces surrounding the building revealed notching in the coral rock near sea level along prominent sub-horizontal weaknesses combined with sub-vertical major fissures extending landward to below and beyond the building.

The distress cracking appeared on all five levels of the building and in the basement. Most was concentrated in the northwest corner, in the basement and on the first three floors. Less severe cracking appeared elsewhere. The cracking typically comprised ~45° oriented flexural shear cracking on both east-west and north-south structural walls. There was also some sub-vertical (~90°) tensile cracking.

Golder carried out numerical analysis (continuum, FLAC, and discrete element analysis, UDEC) on two sections through the northwest of the building. The models

3-D graphical grout take model



included various vertical zones of weakness along the observed pattern of sub-vertical jointing across the site. The models also incorporated the structural modelling of the building shell so that vertical displacements, shear and principal stresses within the walls could be calculated and cracking patterns could then be interpreted, based on the stress trajectories. By comparing the crack patterns from the numerical models with the actual cracking in the building, one could make an in-depth evaluation of the most likely causes of the cracking patterns. Based on the modelling, void creation as well as undercutting of the cliff face (from wave action), in conjunction with a weakened rock mass along the sub-vertical jointing,

The results showed that the building was founded on a highly variable, vuggy, heterogeneous, weak coralline rockmass containing voids, sub-horizontal and sub-vertical fissures and joints. The boreholes also revealed a less friable, less voided and more competent zone of coralline rock at a depth of about 50 ft (16 m). The investigation also found a hardened coralline cap, up to about 10 ft (3 m) thick, around parts of the site including on the remnant coral sea stacks in front of the shore side of the building. This more competent material likely existed over much of the rockmass within the building footprint prior to construction. However, excavation for the basement probably removed most of this cap in the northern

showed the most convincing settlement and cracking patterns in the structure. Foundation degradation was likely exacerbated by migration of fines from natural fissures and void zones within the coralline rock mass during violent sea conditions. The northern half of the structure had a lower foundation (the basement level), which was probably a key factor in the building behaviour. These conditions resulted in the removal of the more competent coralline cap material in this area, higher foundation loads as a result of the additional level, and a founding level in closer proximity to the weak subsurface conditions. These findings were the basis for the remediation design.

Remediation Concepts and Design

Considering the subsurface conditions, and the fact that any remediation would have to be constructed from within and around the existing building, a combination of micropiles and grouting was a probable solution. In March 2007, Geosystems L.P. joined the consultant team to refine the remediation design and to guide contractor selection.

The remediation concept had three main components:

- A barrier to prevent further marine intervention into the subsurface zone beneath the building
- Additional direct support to the foundation on three sides of the building
- Improving the load-bearing capacity of the weak coralline strata below the interior of the northern half of building

The subsurface barrier/seawall design included two rows of 5.5 in (140 mm) diameter micropiles. The outer row of near vertical micropiles was installed on a 15° inclination from the vertical parallel to the sides of the building and extended down into the more competent coralline rock below 50 ft (16 m) depth. The inner row of battered micropiles was installed perpendicular to the sides of the building at inclinations alternating between 30° and 45° from the vertical and depths varying from 30 ft to 60 ft (10 m to 20 m) to extend below the existing building. The top of the micropiles were encased into a reinforced concrete cap/grade beam structurally connected to the existing building footings and/or to the foundation wall. Simultaneous grouting, carried out as part of the micropile installation and in separate targeted grout-only holes, was designed to back-fill the washed out zones and any open and interconnected fissures and fractures. The grout stiffened the in-situ rockmass, reduced void porosity and hence minimized potential future vertical settlement. In addition to the exterior micropile wall, the design included some near vertical micropiles installed within the interior of the building through the basement foundation slab where the wall loads were highest and where the largest measured vertical movement had occurred. These interior micropiles were supplemented by grout-only holes that provided additional void filling and foundation stiffening at key interior locations.

The outer row of micropiles was to be installed first, to create the "seawall" concept as efficiently as was feasible. In addition, wherever possible, split-spaced grouting closure principles were to be adopted in each row so that the micropile installation followed a primary, secondary, tertiary, quaternary, quinary pattern. Larger grout takes (which used a low-mobility grout) were controlled and preferentially restricted to the higher order holes. The smaller grout takes were expected in the quaternary and quinary locations as closure (tightening of the ground) progressed.

Contractor Selection

The schedule was extremely compressed. The site assessment and preliminary remedial design had to proceed during contractor selection, and a fast mobilization to the island was essential. The precise scope of the remediation, and means and methods could only be determined when the work began.

The "fast track" nature of such work tends to place severe strains on project participants. These factors favoured the team working within the framework of an "Alliance" to assure selection of the best contractor, to maintain communications and incorporate problem resolution mechanisms. The Alliance concept also ensured schedule compliance, and equable cost management procedures.

Keys to the Project – the Contractor's Perspective

In a complex project such as the Sandy Cove foundation remediation, there are many nuances in the site conditions and design plan. It is hard to single out only a few items, but we feel there were three main design and construction decisions that were key factors in the project's success.

Concrete cap/grade beam construction

1. Using low mobility grout vs. high mobility grout

High mobility grout (cement and water only) is typically used for micropiles and foundation grouting. With a very pervious foundation material, such as the coralline limestone at this site, using that material could have led to installing massive grout quantities with no assurance of where it would flow. Using low mobility grout with a measurable slump allowed greater control over placement. Low mobility grout includes a significant portion of sand and was batched on-site at a slump of about 4 in. The decision to use this grout saved time and maximized effectiveness.

2. Attaching the micropile cap directly to the structure

There were two micropiles options. One was to use the micropiles as a barrier; the other was to attach the micropiles with a cap beam directly to the condominium structure. By using the latter option for three exterior walls, we were assured that the direct support of the micropiles and pile cap would prevent any future settlement at those locations. If the micropiles had been installed only as a barrier to tie the rock together between the structure and the cliff, the direct benefits of the strength of the micropiles in compression would not have helped prevent settlement.

3. Reinforcing the micropiles to resist bending at the top of the piles

Below the capping beam, a bending moment transferred to the pile. By including a short section of steel casing at the top of the micropiles, any bending moments transferred to the piles by the structure are carried by the casing. A pile with only a steel bar would not have been able to carry the requisite bending moments and could have deflected or bent. The casing/pipe reinforcement assured the stiff response of the micropile system with the cap beam.

The engineer compiled a data summary and a conceptual design that was circulated to a small group of specialty contractors with the requisite resources and experience. These contractors then submitted a preliminary assessment report that included their commitment to working within the Alliance framework. Three potential bidders were invited to site visits, technical meetings and interviews. Hayward Baker Inc., was selected and committed to a prompt mobilization. Procuring the most appropriate contractor was a key factor in the quality and pace of work, as was the highly functional communication framework.

Monitoring

The on-site team recorded the conditions during drilling and the volume of grout injected at discrete depth intervals in each hole. The geological model developed as part of the remediation design phase, and the numerical modelling was adjusted and refined as construction proceeded. Design layouts were refined in near real-time as additional subsurface information was obtained. Records were updated daily and the grout-take data was tracked using 2-D and 3-D graphical models so that the weakest/most voided conditions in the subsurface could be readily identified. These areas were then targeted with additional grout-only holes during production. At completion, data had been acquired from the drilling and grouting of 174 micropiles, during which 750 m^3 (1000 yd^3) of low-mobility grout was injected into the voided areas of the foundation around the perimeter and below the interior of the building.

Throughout construction and following completion, the building was monitored for settlement, tilt and crack spreading. This instrumentation included electro-levels, tiltmeters, crack gauges, precise levelling points and prisms. These data showed that localized areas of the building initially settled as a result of the drilling/injection/flushing/disturbance to the weak subsoils by the micropiling operations, followed by upward movement as a result of the pressure grouting. A trend of increasing stabilization was observed throughout the remediation program, as each area of the building was underpinned and grouted.

Conclusions

The building foundation remediation and improvement included the following:

- Installing a 290 ft (88 m) long subsurface 'seawall' barrier around three sides of the building

Drilling for micropile installation on the south side of the building

Drilling for micropile installation with restricted access on building's west side

- Underpinning three sides of the building with 137 – approximately 70 ft (21 m) long, 5.5 in (140 mm) diameter micropiles
- Indirectly supporting the heavily loaded interior walls below the northern part of the building with 37 – approximately 65 ft (20 m) long, 5.5 in (140 mm) diameter micropiles
- Grouting voids and interconnected fissures/fractures in the subsurface below the building

The micropiling and infill grouting program achieved its two main design objectives of:

- Creating a 'subsurface seawall' to prevent further wave-induced flushing and migration and loss of fine material from the subsurface below the building
- Improving the foundation rockmass to effect an overall stiffening of the subsurface that increased the load-bearing capacity of the originally weak and voidy, coralline rockmass.

The fact that no damage (or even re-activation of earlier patterns of adverse cracking) occurred in response to the passage of Hurricane Dean (in August 2007, toward the completion of the remediation works) or in response to an earthquake that occurred shortly following completion of the remediation in November 2007 clearly demonstrates the effectiveness of the grouting and micropiling.

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