Columnar Basalt – Vibration Study and Preservation Methods at Mumbai, India

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ABSTRACT

The Gilbert Hill is situated west of the Andheri railway station on western railway line in Mumbai, India. The present hill is practically a vertical monolith that rises about 60 meters (200 ft) above the surrounding ground level. The hill displays beautiful vertical columnar jointing that extends from the top to the bottom. Because of its rare and almost unique occurrence the hill with columnar joints is important geologically and historically. Hence, this hill needs to be preserved. The jointing is very well exposed in the western, northern and eastern parts. In the southern part there is rolled down debris that covers the exposure of the columnar jointing. The paper deals with the effect of vibrations caused by the construction equipment on the jointed rock body, for which vibration studies have been carried out. The propagation of waves (vibrations) at various locations (points) in the area resulting from use of heavy construction equipment like vibratory roller, rock breaker, etc was studied. The induced Peak Particle Velocity (PPV) is then compared with the tolerable PPV specified in the available literature. Based on the results of vibration studies carried out measures to protect, preserve and conserve the Gilbert Hill are discussed.

INTRODUCTION

The Gilbert Hill is practically a vertical monolith that rises about 60 meters (200 ft) above the surrounding ground level. The hill displays beautiful vertical columnar jointing. Since columnar jointed structure is rare and only two to three such structures are present in the world, Gilbert hill can be considered as a geological monument worth preserving and may be made into a tourist attraction site. Because of its rare and almost unique occurrence the hill with columnar joints is important geologically and historically.

The rocks in the monolith are of volcanic origin formed by volcanic eruption at the end of Mesozoic era about 65 million years ago. The basalt plug of the Gilbert hill shows very distinct columnar jointing that extends from the top to the bottom of the hill. The jointing is very well exposed in the western, northern and eastern parts of the hill. In the southern part there is rolled down debris that covers the exposure of the columnar jointing. The present extent of the basalt plug is restricted to the Gilbert Hill while in the surrounding areas there are outcrops of the stratified tuffaceous breccia or hyaloclastite.

Quarrying was permitted in Gilbert Hill area during 1960s and part of the hill was cut without knowing its importance. Also recent development and construction activity in the area surrounding the hill could have endangered the stability of the remaining hill portion.

In this paper, causes of failure of the rock slopes and measures to protect, preserve and conserve the Gilbert Hill are discussed. The paper also suggests the measures to prevent and / or to reduce seepage of water in joints and prevent or at least mitigate loss of property and human lives. The paper also deals with the effect of vibrations caused by the construction equipment on the jointed rock body, for which vibration studies have been carried out. The propagation of waves (vibrations) at various locations (points) in the area resulting from use of heavy construction equipment like vibratory roller and rock breaker was studied. The induced Peak Particle Velocity (PPV) is then compared with the tolerable PPV specified in the available literature.

GENERAL GEOLOGY

The geology of the area is part of the Deccan Volcanic Province, which is made up of a number of subaerial basaltic lava flows, which occur as practically horizontal flow basalts. The Deccan Volcanic Province extends over a very large area covering the major part of Maharashtra State and also extends into the neighbouring states of Gujarat, Madhya Pradesh, Andhra Pradesh and Karnataka and was formed about 65 to 67 million years before present. There are mainly two types of lava flows, viz., (a) Simple Lava flow basalt and (b)

Fig. 1. View of Gilbert Hill

Fig. 2. View of columnar joints

Compound lava flow basalts. Some of the simple lava flow basalts that are generally made up of compact basalt, display columnar joints (fractures developed due to contraction of the rock which solidifies at above 1000° C and thereafter undergoes contraction during the cooling process) that are usually restricted to the upper and lower part of the flow basalt. They are generally described as the Upper Colonnade Zone and the Lower Colonnade Zone with an intermediate zone that does not display columnar jointing that is described as the Entablature Zone. The Compound lava flow basalts invariably show amygdaloidal character, with the gas cavities (vesicles) filled up by secondary minerals such as, zeolites, calcite, chlorite and silica. Such lava flow basalts do not display columnar jointing.

In the western coastal part the lava flows show a westerly dip varying from 5° to 15°. Moreover in the western coastal belt around Mumbai, Salsette and Bassein the lava flows show subaqueous character in the form of spilitic pillow lavas and subaqueous flow breccias and tuffaceous breccias that are described as hyaloclastites. Sedimentary intertrappean beds, such as shales, which are even fossiliferous, often separate these subaqueous lava flows. In addition, to the extrusive flow basalts and hyaloclastites, there are a number of intrusive bodies mainly in the form of dykes of dolerite and basalt as well as some trachytic and granophyric intrusives along with some rare types of alkaline rocks, such as lamprophyres and nepheline syenites. Majority of the dykes along the western coastal belt, extending from Balsar in the north to Murud-Janjira in the south, show a north-south trend.

GEOLOGY AT THE SITE

The plot under investigation is situated in the west central part of Salsette Island, about 500 meters west of the Andheri railway station (suburban western railway). The rock type encountered in the Gilbert hill is mainly compact basalt which is intrusive into the stratified tuffaceous breccia that shows distinct westerly dip (Fig. 1 and Fig. 2). The basalt intrusion is in the form of a nearly circular body that was originally much larger in diameter as compared to what exists today. It is in the form of a practically vertical monolithic body that rises almost 60 meters above the surrounding ground (Fig. 3). Similar columnar jointed intrusive basalt also outcropped in Amboli Hill, west of Jogeshwari Railway Station. The latter intrusive body has been described by Tolia Nita & S. F. Sethna (1990) as a lopolithic intrusion. Unfortunately the entire basalt outcrop at Amboli Hill has been quarried and now there are only a few traces of the basalt seen in the area. There is no evidence of the Gilbert hill basalt being a lopolithic body, as we only see the vertical cylindrical body **which represents a volcanic plug.**

The basalt plug of the Gilbert hill shows very distinct columnar jointing that extends from the top to the bottom of the hill. The jointing is very well exposed in the western, northern (Fig. 2) and eastern parts of the hill. In the southern part of the hill there is some amount of rolled down debris that covers the exposure of the columnar jointing (Fig. 3). The present extension of the basalt plug is restricted to the Gilbert hill while in the surrounding areas there are outcrops of the stratified tuffaceous breccia or hyaloclastite. The Gilbert Hill basalt has been dated by Dr. Mike Widdowson, of the Open University, Milton Keneys, U.K. and it is 60.5± 1.2 million years old.

Proposed Study: In this paper effect of vibration on stability of the columnar jointed rock mass is studied and suggestions for the preservation of this majestic geological monument that

Fig. 3. Plug of basalt intrusion

Fig. 4. Debris after heavy rain fall

is one of its kind in India. A similar old volcanic plug showing columnar jointing also occurs in New Mexico, and is described as “Ship Rock”, that outcrops in the American desert.

THE NEED FOR VIBRATION STUDY AT GILBERT HILL

Construction activities have the potential to produce vibration levels that may be annoying or disturbing to humans and may cause damage to structures. Architectural and even structural damage to existing structures surrounding a site could occur if appropriate precautions are not taken.

Quarrying was permitted in the Gilbert Hill area during 1960s and the rock is cut without knowing its importance. Also the recent development and construction activity in the surrounding area may have endangered the stability of the remaining hill portion. The hill shows columnar jointing. Due to quarrying the joints may have opened out. Seepage of water in joints during rains would have enhanced the joint separation. Added to this, use of heavy construction equipment in the vicinity of the hill may induce vibrations thereby widening the joint aperture.

Since the stability of the monolith can be disturbed by vibrations caused by use of heavy construction equipment, the present paper discusses the effect of vibrations.

BASIC MECHANISMS OF ROCK SLOPE FAILURE

The shear stresses generated in an excavated rock slope are usually low in comparison with the shear strength of the intact rock material. Pre-existing discontinuities in the rock mass may have sufficiently low strength for failure to occur along them. A common approach is to assume full joint community and to neglect any contribution to strength made by sections of intact rock along potential failure surfaces. This is conservative and is applicable to most engineering situations.

By comparison, the economical design of mine excavations and temporary civil works impose the condition that slopes should be closer to limiting equilibrium. For this case, multiple failure modes of rock and rock joints may be considered.

The principal types of failure relevant to rock slopes are rotational, translational and toppling modes (Richards et al. 1978). These are idealized and combinations of any of these modes may be possible in any given situation. Because the hill reveals steep slope and columnar jointing, toppling failure is the most likely mode.

Toppling Failures

Toppling failures involve the overturning of blocks of rock and are generally associated with steep slopes and sub-vertical jointing patterns. The overturning mechanism may lead to deep-seated rotational failures through loosening of the rock mass if allowed to progress.

Toppling of individual blocks is governed by joint spacing and orientation. The criteria for toppling failure have been set down for both two and three dimensional modes of failure. The condition for stability is that the resultant force must be within the central two-thirds of the base of the block. Hydrostatic forces must be within the central two-thirds of the base of the block.

SHEAR STRENGTH OF ROCK JOINTS

The shear strength of rock joints is derived from two main components:

1. A basic frictional resistance for the joint surfaces. This basic friction angle is that obtained in a smooth, planar surface of the rock material. In general, it is equal to the residual strength of the joint.
2. An additional resistance caused by irregularities on the joint surface. These surface features give rise to an apparent cohesion or an increase in the friction angle over that of a planar surface.

DETAILS OF VIBRATION STUDIES

The Peak Particle Velocity (PPV) was measured using acceleration pick ups, Cathode Ray Oscilloscope (CRO) and data logging software at various locations shown in (Fig. 6). The PPV was measured simultaneously at two locations. The first location measured the PPV immediately next to the source (taken as reference or base vibration) and the second measurement was taken at a designated distance from the source. These measurements not only give absolute values for comparison but also give the damping of vibrations. The PPV was also measured on the rock body.
The vibrations were generated by

a) Road roller (8 tonne static weight and 32 tonnes under dynamic conditions) and
b) Rock breaking equipment.(L & T make)

These equipment were chosen for the study as representative of the construction activity and because it induces maximum vibrations.
PPV values at various locations are tabulated in Tables 1 & 2.

<u>Procedure for Vibration Study</u>

Figure 5 shows the experimental set-up and data recording at site. The location plan where the vibration study is conducted is shown in Fig. 6. Acceleration pick up mounted on rock is shown in Fig. 7. The acceleration pick ups are placed on either steel plate or well compacted concrete.

- The propagation of waves (vibrations) at various locations (points) in the area resulting from use of heavy construction equipment like vibratory roller and rock breaker was to be studied.
- Points were marked on a centre line at 5m distance. The centre line was marked between Gilbert Hill and the Construction site. (shown in location plan Fig. 6).
- The heavy construction equipment; the rock breaker and the roller were made to vibrate at these points.
- The points where the effect was to be compared were situated at a distance 5 m perpendicular to the centre line.

Fig. 5. Experimental set-up at site.

- The induced Peak Particle Velocity (PPV) is then compared with the tolerable/permissible PPV specified in the available literature.
- The induced particle velocity was measured with the help of pick-ups.
- The signal is then magnified using a charge amplifier (Fig. 8) and then recorded using software for the Digital Oscilloscope.
- The amplifier is connected to an oscilloscope (Fig 8.) which records the readings which are then recorded on a laptop directly connected to it.
- The software is used to exactly find the amplitude of vibrations from the graph.
- The maximum amplitude in each graph taken for every set of readings of vibrations is then recorded and tabulated.
- According to the safety limits the permissibility of vibrations is decided.

ANALYSIS OF MEASUREMENTS

The PPV measured at different locations has been compared with the permissible PPV value of 2 mm/sec. (TSR, 2003 & FTA, 1995)
Studies reveal that-
a) PPV resulting from the use of rock breaker are higher that those resulting from the use of vibratory roller.
b) As the distance from the source increases the vibrations dampen and PPV value reduces.
c) Within a distance of about 5 m. the damping is substantial.

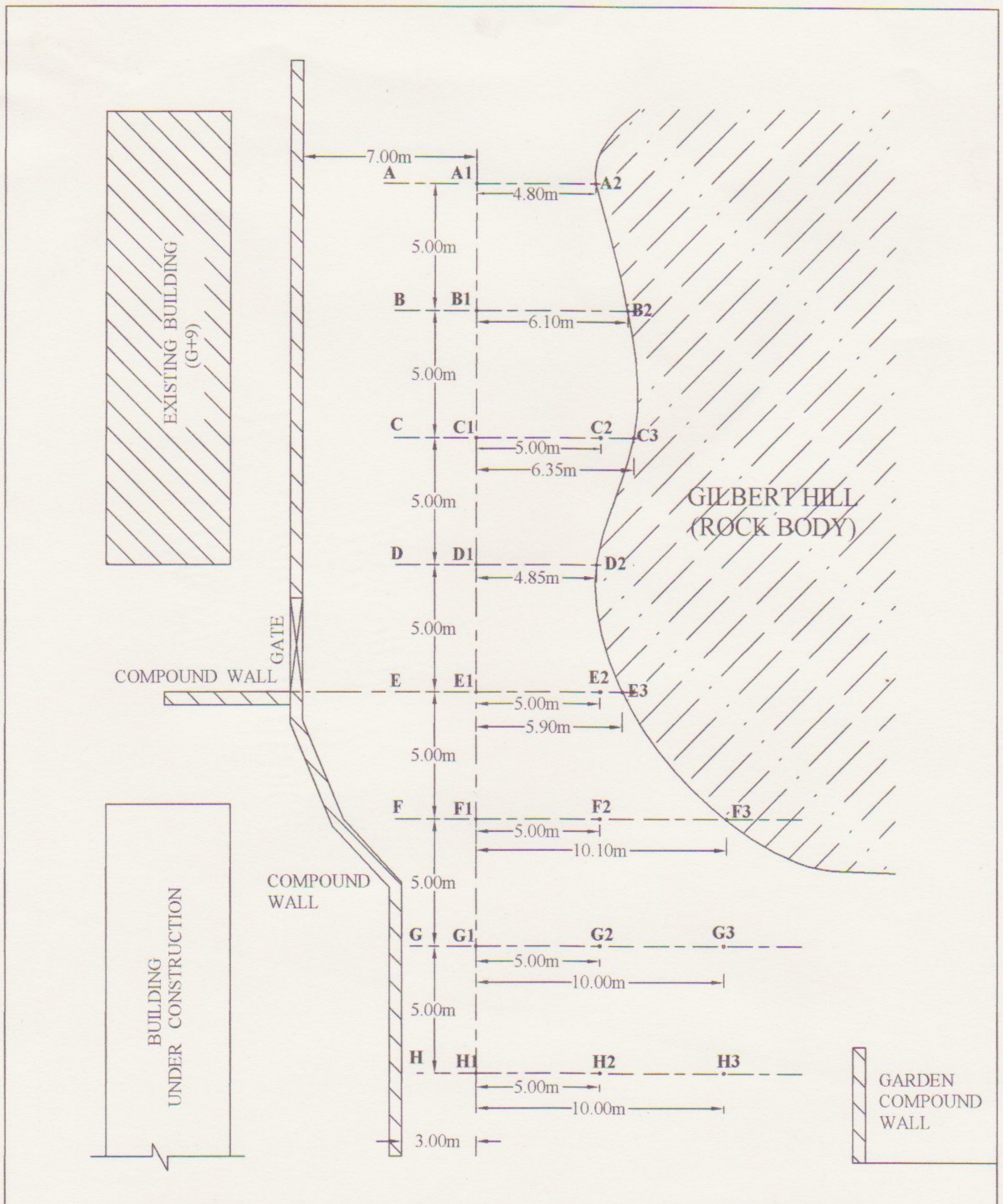

Fig. 6. Location plan for vibration test at Gilbert hill

Fig. 7. Acceleration pick-up on rock.

d) The PPV measurements indicate that construction equipment (road roller or rock breaker) does not cause harmful vibrations to the rock body at the site if the source of vibrations is at least 5 m. from the rock body.

Although most commonly used construction equipment does not cause vibrations more than the permissible PPV, in view of the geological importance of the rock body, protection and conservations measures need to be taken. Various measures to protect and conserve the hill outlined in the following section.

INSTRUMENTS USED FOR VIBRATION STUDY

Main instruments used for this study are

1) Charge amplifier 2) Oscilloscope
3) Acceleration pick-ups 4) Data logger

<u>Charge Amplifier</u> — Type 2635 (Fig. 8).

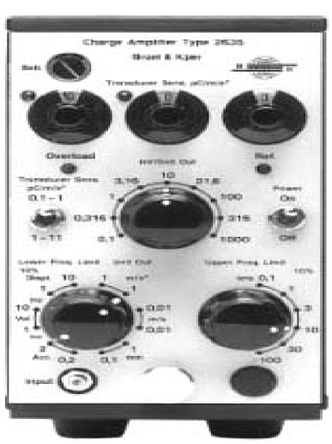

Fig. 8. Charge Amplifier — Type 2635

<u>Uses of Charge Amplifier</u>

1) Field and laboratory measurement of vibration in terms of acceleration, velocity and displacement together with piezoelectric accelerometer and voltmeter or measuring amplifier
2) Field recording of vibration and other signals together with portable tape recorders and level recorders
3) Underwater sound measurements with hydrophone
4) Mechanical impedance measurements

<u>Oscilloscope</u>-Analog and Digital HM1507-3 (Fig. 9)

Fig. 9. Oscilloscope-Analog and Digital HM1507-3

DIGITAL	ANALOG
Refresh, Roll, Single, Envelope	2 × DC-150 MHz -1mV
Peak Detect Average and XY	identical Channels
Modes	Dual Timebase
200MS/s Real Time Sampling	Triggering upto 250MHz at
2k Per Channel Memory	0.5 Division
2 × 2k Reference Memory	Delay Line Noise Reject
Pre and Post triggering	alternate triggering
180Hz Screen Refresh	Active TV Sync Separator
Multifunction Interface (Option)	Component Tester
(IEEE-Bus RS232 & Centronics)	

PEAK PARTICLE VELOCITY (PPV)

Measurements of vibration used in this evaluation are expressed in terms of the peak particle velocity (PPV) in the unit of millimeters per second. The PPV, a quantity commonly used for vibration measurements, is the maximum velocity experienced by any point in a structure during a vibration event. It is an indication of the magnitude of energy transmitted through vibration. PPV is an indicator often used in determining potential damage to buildings from stress associated with blasting and other construction activities.

Table 1 shows the recorded voltage and the evaluated PPV due to road roller. The evaluated PPV at different locations due to rock breaker is in Table 2.

RECOMMENDED CONSTRUCTION VIBRATION LIMITS

To evaluate the effect of vibrations on the stability of the hill the following are considered as guidelines.

- The limit of 50 mm/s (2 in/sec) ppv is frequently applied to construction vibrations and still widely viewed by many engineers as stringent enough to prevent damage to most surrounding structures regardless of age or fragility (Sedowic, 1984).
- For ruins and ancient monuments, as well as historical buildings or structures in poor condition, Caltrans recommends an upper limit of 2.0 mm/s (0.08 in/sec) for continuous vibrations.

Table 1 PPV due to Road Roller

LOCA-TION	DISTANCE OF	TRIAL 1		TRIAL 2	
	LOCATION FROM	RECOR-DED	EVALU-ATED	RECOR-DED	EVALU-ATED
	SOURCE (m)	VOLTAGE (mV)	PPV (mm/sec)	VOLTAGE (mV)	PPV (mm/sec)
A1	0	0.0375	3.75		
A2*	4.8m	0.0125	1.25		
B1	0	0.075	7.5		
B2*	6.1	0.0032	0.32		
C1	0	0.0625	6.25	0.0469	4.69
C2	5.0m	0.0031	0.31		
C3*	6.35m			0.0016	0.16
D1	0	0.0158	1.58		
D2	4.85m	0.0016	0.16		
E1	0	0.0937	9.37	0.0314	3.14
E2	5.0m	0.0063	0.63		
E3*	5.9m			0.0063	0.63
F1	0	0.0937	9.37	0.0937	9.37
F2	5.0m	0.0063	0.63		
F3*	10.10m			0.0031	0.31
G1	0	0.0937	9.37	0.0937	9.37
G2	5.0m	0.0125	1.25		
G3	10.0m			0.0063	0.63

* Denotes location is on base of rock body

REMEDIAL MEASURES

Rock slopes are often designed for overall stability and an allowance made for redesign and stabilization of local areas. For an economical design, about 10% of the slope area may require some form of treatment. Some of the commonly used methods of enhancing the stability of rock slopes include:

1. Alteration of slope geometry
2. Structural support
3. Dental treatment
4. Drainage improvement

Table 2. PPV due to Rock Breaker

Loca-Tion	Distance of	Trial 1		Trial 2	
	Location From	Recorded	Evalu ated	Recorded	Evaluated
	Source (m)	Voltage (mv)	PPV (mm/Sec)	Voltage (mv)	PPV (mm/Sec)
A1	0	0.3907	39.07		
A2*	4.8m	0.0094	0.94		
B1	0	0.3313	33.13		
B2*	6.1	0.0063	0.63		
C1	0	0.7437	74.37	0.9686	96.86
C2	5.0m	0.0063	0.63		
C3*	6.35m			0.0031	0.31
D1	0	0.5469	54.69		
D2	4.85m	0.0031	0.31		
E1	0	0.1561	15.61	0.0781	7.81
E2	5.0m	0.0156	1.56		
E3*	5.9m			0.0047	0.47
F1	0	0.75	75	0.7967	79.67
F2	5.0m	0.0063	0.63		
F3*	10.10m			0.0031	0.31
G1	0	0.6876	68.76	0.5625	56.25
G2	5.0m	0.0281	2.81		
G3	10.0m			0.0094	0.94
H1	0	0.5001	50.01	0.5469	54.69
H2	5.0m	0.0438	4.38		
H3	10.0m			0.0094	0.94

* Denotes Locations is on Base of Rock Body

RECOMMENDATIONS FOR GILBERT HILL

Based on the visual inspection of the joints system and vibration studies carried out, measures to prevent further deterioration and conservation of the hill are as under.

1. Pave the area at the top to prevent seepage of water in to joints which cause widening of joints and subsequent toppling.

2 Provide properly designed storm water drain (SWD) at the top of the hill. This should be done without cutting rock surface.

3. Prevent any further excavation of hill sides and which would result in steepening of slopes or removal of support.

4. Create an area which should be turfed with a suitable fencing all round the base of the existing hill. No construction activity should be permitted in this area.

5. The UCR retaining wall near the Gaondevi Trust office should be dismantled and reconstructed with proper design and drainage provisions. Length of the wall should be increased. This would protect the flow of soil cover on the rock slope.

6. Gunite sides to prevent further erosion and weathering. However weep holes should be provided to facilitate drainage to prevent development pore pressure. This work is proposed on the South and South East side where there is soil overburden.

7. Adopt construction methods for the near by roads, that would eliminate use of heavy equipment. Paver blocks which can be laid without heavy equipment should be considered for the road.

8. Provide catch fence for rock fall protection.

Probable measure can also be to declare the Gilbert hill as a protected structure / monument and convert it into a place of tourist attraction to prevent its further deterioration and conservation.

CONCLUSIONS

The existing intrusive rock body exhibiting columnar jointing at Gilbert Hill is a world acclaimed geological phenomenon. The tuffaceous breccia immediately surrounding the intrusive rock body is also of utmost importance as it supports the jointed basalt rock. The protective measures mentioned in this paper are for the existing intrusive, columnar basalt and tuffaceous breccia immediately surrounding it.

a. Vibration studies show that PPV due to the use of road roller or rock breaker is within permissible limits provided the equipment is beyond 5 m from the rock body.

b. Measures for protection, preservation and conservation have been outlined.

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