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Strengthening and Performance of a Cane Cutter Foundation

by

Krishen Kumar*

Gopal Ranjan*

Introduction

The cane-cutter at a sugar factory consists of a heavy shaft on which 88 blades, each weighing 0.15 KN are mounted in 11 planes along the axis of the shaft. A flywheel is also attached to the shaft. The cane-cutter is driven by a 450 hp motor weighing 20 kN and operating at a speed of 560 to 600 rpm.

The foundation for the cane cutter was constructed in 1977 and was tested under very severe condition by removing three blades along the same line parallel to the axis of rotation. The foundation was not constructed in a single pouring whereby cold joints were formed. During the test severe vibration amplitudes were observed. Undesirable vibrations were felt as far away as 30 m. Also, during the test the pedestal supporting the motor end of the cutter developed cracks at one of the cold joints at about 2.85m below the base of the motor. For operating the cutter during the crushing season of 1977-78, a temporary stitching of the pedestal was carried. The stitching consisted of welding a RSJ frame suitably wedged-two horizontal frames of ISMB 250 all around the pedestal at a spacing of 1.0 m one placed above and other below the cracks at a distance of 50 cm connected by a total of 14 pieces, 6 of them ISMB 250 and 8 ISMB 200 were used.

Subsequently tests for vibration measurement and assessment of effectiveness of stitching were carried out with all the blades in position and also with one of the blades removed. An acceleration amplitude of 400 cm/sec^2 was observed on pedestal under a speed of 600 rpm with one blade removed showing an amplitude of 1 mm, which was considered rather high.

Keeping in view the urgency of remedial measures and time constraints, it was decided to increase the foundation dimensions suitably and

*Professor of Civil Engineering, University of Roorkee, Roorkee-247 667, India.
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to provide adequate reinforcement properly connected to the old reinforcement. The foundation after taking these measures is shown in Fig. 1. The machine was used for crushing of cane during the subsequent season and no distress to foundation was noted.

Strengthening of Foundation for Increased Capacity

Later, in 1987 it was proposed to increase the power of the cane cutter by adding another driving motor of 250 hp capacity at the other end (flywheel side) of the shaft, necessitating extension of the pedestal underneath by 1.5m (Fig. 2). The outer foundation-bolt for this motor had its central axis at about 80 mm inside the face of the pedestal, while the pocket for the bolt extended a little beyond the face. The foundation thus needed to be further strengthened to ensure that vibration levels do not exceed the permissible limits.

Although essentially one blade should break at a time, the design criterion is to consider the maximum unbalanced force when two blades in a horizontal line, that is, at the same radial orientation, are supposed to have broken. The manufacturers have suggested a design where an equivalent static lateral load of 3 tonnes with a dynamic factor of 2.5 is to be considered, apparently for checking the stresses in the foundation under the critical condition of two broken blades in a line.

Strengthening Measures

Before taking up the strengthening measures, it was felt desirable to assess the health of existing foundation. Accordingly, measurements of vibration at different locations of the foundation were taken in July 1987 using vibration meter of IRD Mechanalysis model 810. These are summarised in Tables 1 & 2 for the horizontal and vertical directions.

To strengthen the smaller pedestal for accomodating the new 250 hp motor and to provide an additional working space 1.5 m wide, it was decided to add 0.7 m thick concrete with a 0.8 m cantilever projection at the top of this pedestal as shown in Fig. 2. The best way of ensuring bond of the additional concrete with the existing concrete was to jacket the pedestal by providing concrete all around. Thus 300 mm thick concrete on the remaining three faces of the pedestal was suggested, with steel bars made as continuous rings by lapping them sufficiently (63 ϕ) at the splicings. The additional concrete thickness could be reduced to 200 mm on the inside face under the cutter without any detrimental effect.

With the increase in mass of the foundation, it shall also become necessary to increase the width of the base raft, thereby increasing the stiffness, so that the system's natural frequencies of vibration in the two coupled translational and rocking modes remain close to the existing values

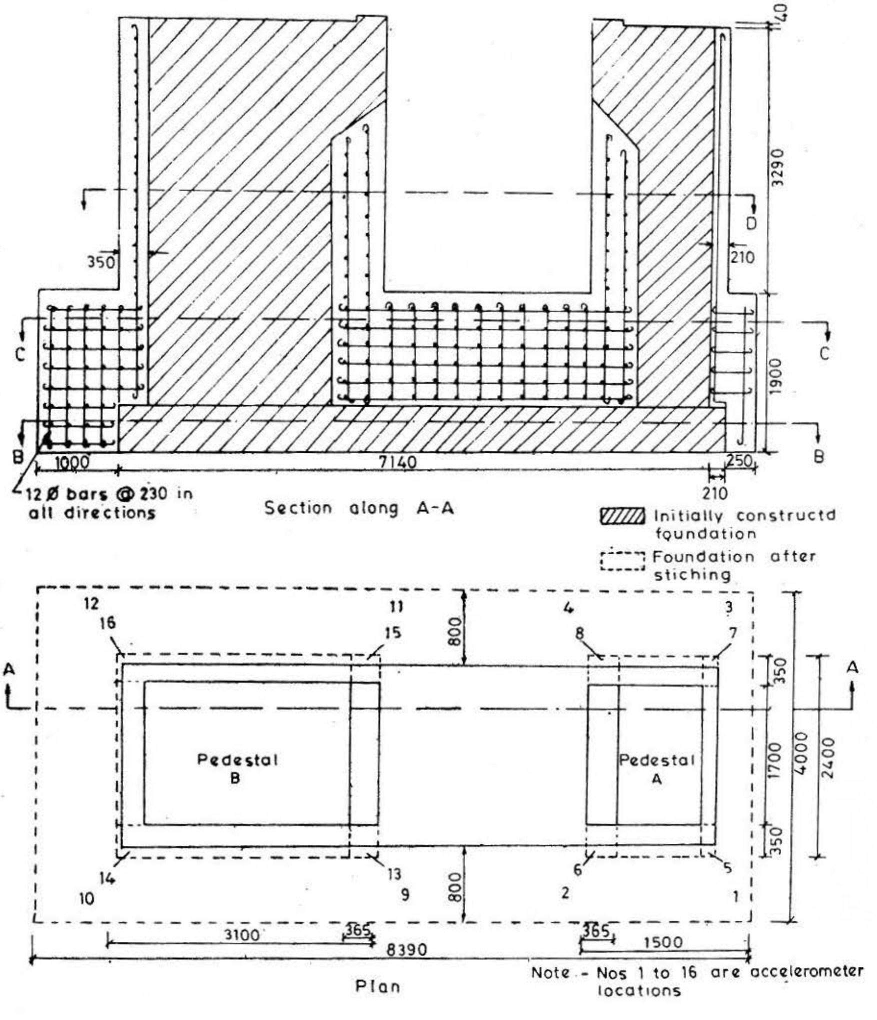

FIGURE 1 Foundation before and after Remedial Measure of 1987

of 283 and 754 cpm, which are nearly ideally spaced with respect to the operating speed of 560 to 600 rpm. Thus the vibration amplitudes will remain close to the present values, and hence safe.

Use of expanding cement, like shrinkkomp, was considered undesirable since shrinkage helped tighten the grip of concrete jacket on the pedestal. Concrete grade M-15 made with ordinary Portland cement and guaranteed tor-steel grade Fe-415 were recommended for use.

TABLE 1

Horizontal Acceleration Amplitudes Divided by 'g'

location	With two blades removed and no cane load		Under normal cutting operation		
	Before R.M.+ one motor	After R.M.++ two motors	After R.M.+ one motor	After R.M.* two motors	After R.M.** two motors
Block-A					
1	0.10	0.12	0.12	0.13	0.13
2	0.11	0.08	0.08	0.08	0.07
3	0.09	0.14	0.12	0.11	0.12
4	0.14	0.06	0.05	0.07	0.07
5	0.45	0.22	0.30	0.25	0.30
6	0.60	0.50	0.36	0.34	0.34
7	0.60	0.26	0.40	0.25	0.20
8	0.90	0.35	0.30	0.32	0.32
Block-B					
9	0.04	—	0.07	0.07	—
15	0.04	—	0.07	0.07	—
16	0.14	—	—	—	—

\+ R.M. indicates remedial measures

* Soon after the remedial measures

** After five months of remedial measures

++ After eight months of remedial measures

It was necessary to carry the bars all around in the extension of the base raft also, thus providing closed and continuous rings. The close rings helped in keeping the new concrete pressed against the old concrete and prevent loosening of the bond between the two concretes, which generally needs special treatment (Kumar et al. 1982).

Data Used in the Analysis

The following data on soil characteristics has been used for computing the amplitudes of vibration of the foundation:

Safe bearing capacity at site = 100 kN/m^2

Coeff. of elastic uniform compression of soil, C_u = 30,000 kN/m^3

TABLE 2

Vertical Acceleration Amplitudes Divided by 'g'

Location	With two blades removed and no cane load		Under normal cutting operation with all blades intact		
	Before R.M.+ one motor	After R.M.++ two motors	After R.M.* one motor	After R.M.* two motors	After R.M.** two motors
Block-A					
1	0.23	0.07	0.12	0.13	0.13
2	0.08	0.08	0.08	0.08	0.04
3	0.08	0.14	0.14	0.15	0.12
4	0.08	0.06	0.06	0.04	0.05
5	0.95	0.40	0.36	0.50	0.35
6	0.76	0.30	0.25	0.22	0.22
7	0.76	0.50	0.40	0.46	0.46
8	0.52	0.30	0.30	0.34	0.30
Block-B					
9	0.04	0.50	0.07	0.06	—
15	0.25	—	—	—	—
16	0.32	—	—	—	—

\+ R.M. indicates remedial measures

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Coeff. of elastic uniform shear, $C_\tau = 0.5\ C_u$ = 15,000 kN/m³

Coeff. of elastic non-uniform compression, $C\phi = 2.0\ C_u$ = 60,000 kN/m³

Unit weight of concrete = 24 kN/m³

Operating speed of machine = 560 to 600 rpm

Weight of one blade of cane cutter = 0.15 kN

Total number of blades = 88

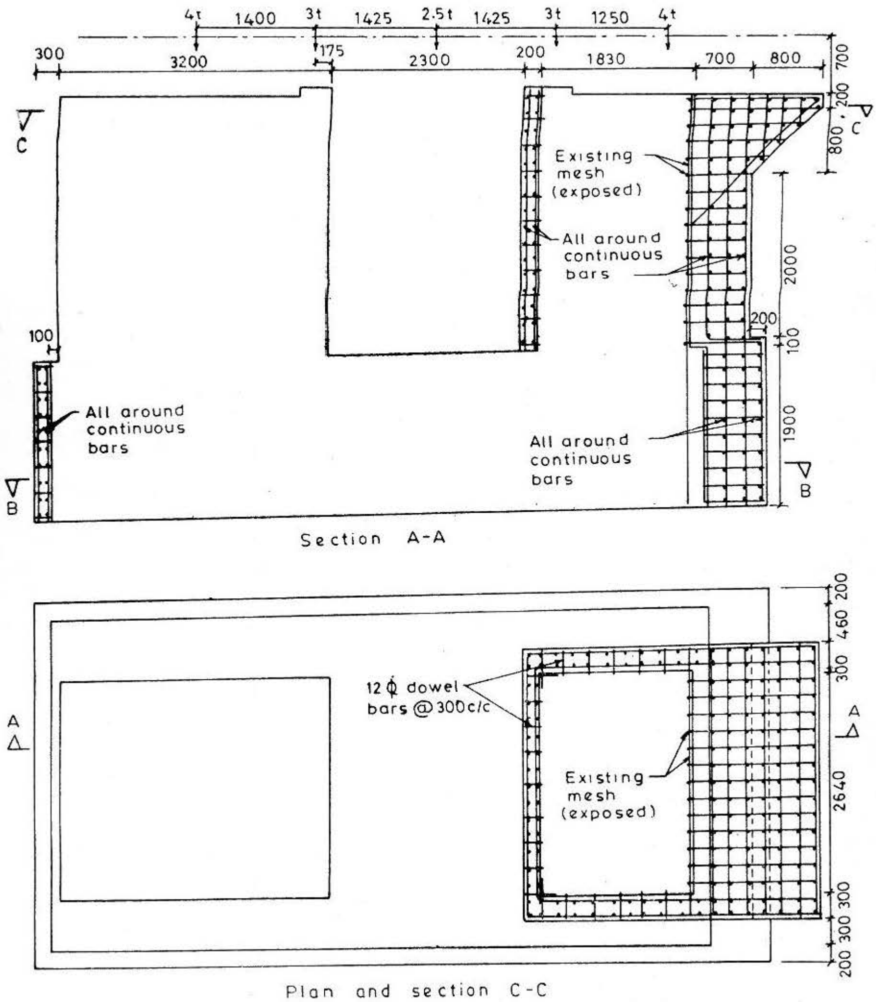


FIGURE 2(*a*) Additional Concrete and Reinforement to Strengthen Existing Foundation.

Distance of CG of blade from axis of rotation = 600 mm

Permissible amplitude of vibrn. under normal running = 0.12 mm

Permissible amplitude of vibrn. for computing stresses = 0.60 mm

Design eccentricity in the rotation components = 0.16 mm

The permissible amplitudes of vibration and design eccentricity have been adopted from Major (1980) and I.S. Code 2974-1979 Part IV.

Analysis for Horizontal Vibrations

Proposed increase in the size of the smaller pedestal and the base raft is shown in Fig. 2. Vibration amplitudes have been computed for the revised size of the foundation to ensure its safety under the normal operating condition as well as the two broken blades condition.

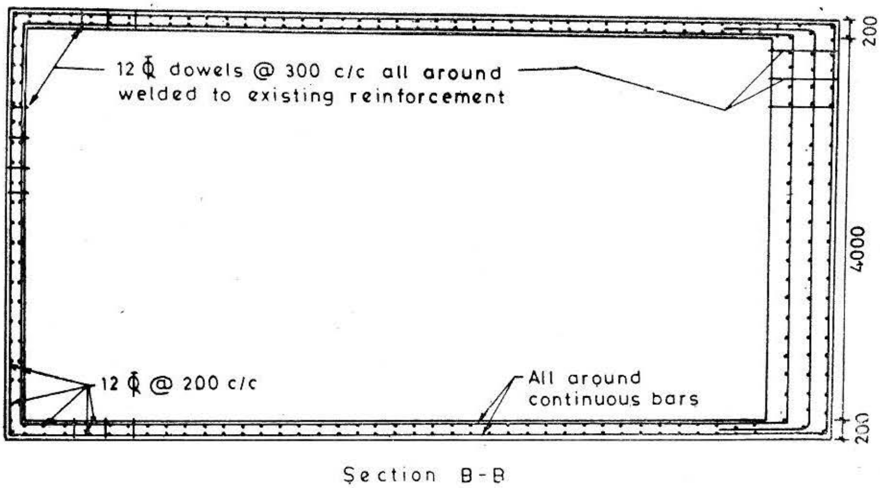


FIGURE 2(b) Additional Contrete and Reinforcement to Strengthen Existing Foundation

Data Used in the Analysis

(*a*) The weights of various components are:

(*i*) Motor 450 hp	=	40 kN
(*ii*) Shaft, flywheel & blades	=	80 kN
(*iii*) Motor 250 hp	=	40 kN
(*iv*) Foundation base raft, pedestals A, B and cantilever platform	=	3070 kN
Total weight, W	=	3230 kN
Mass, m	=	330 kN-s²/m

(*b*) Eccentricity along the axis of the cutter $< 2\%$

(*c*) Eccentricity at right angles to the axis $< 1\%$

(*d*) Height of CG of the system above base, L $= 2.22$ m (*e*) Height of axis of shaft above base of foundation, H = 5.70 m

(*f*) Mass moment of interia about the axis parallel to the axis of shaft and passing through the CG, M_m = 1250 kN-m-s²

(*g*) Mass moment of interia about the axis parallel to the axis of shaft and passing through the centroid of the base contact area, M_{mo} = 2870 kN-m-s²

Analysis for Frequency

$$\text{Ratio, } \gamma = M_m/M_{mo} = 125/287 \qquad = 0.435 \text{ i.e.} < 1$$

$$f_{nx}^2 = \frac{C_\tau\ A}{m} = \frac{15000 \times 4.4 \times 8.73}{330} = 1748\ s^{-2}$$

$$f_{n\phi}^2 = \frac{C_\phi\ I - WL}{M_{mo}} = 1293\ s^{-2}$$

Since ratio, γ is less than 1, the frequency equation can be written as:

$$f^4 - \left(\frac{f_{nx}^2 + f_{n\phi}^2}{\gamma}\right) f^2 + \left(\frac{f_{nx}^2\ f_{n\phi}^2}{\gamma}\right) = 0 \tag{1}$$

Substituting the values

$$f^4 - \left(\frac{1748 + 1293}{0.435}\right) f^2 + \frac{1748 \times 1293}{0.435} = 0$$

Thus,

$f_{1,2}$ = 20.08 rad/s; 78.39 rad/s

= 278 cpm; 749 cpm

f = 600 rpm = 600 × 2/60 rad/s = 62.83 rad/s

Analysis for Amplitude

$$\Delta(f^2) = m\ M_m\ (f_1^2 - f^2)(f_2^2 - f^2) = 2.81 \times 10^{:2} \tag{2}$$

Unbalanced force generated with 2 knives removed in the same horizontal line,

$$P_x = 2 \times \frac{0.15}{9.8} \times 0.600 \times \left(\frac{600 \times 2\pi}{60}\right)^2 = 72.5\ kN$$

Moment generated about CG, M_y = 72.5 (5.70-2.22) = 252.2 kN-m

Amplitudes of Horizontal Vibrations

$$a_x = [C_\phi\, I - WL + C_\tau\, AL^2 - M_m f^2)\, P_x + C_\tau\, AL\, M_y]/\Delta\,(f^2) \tag{3}$$

Substituting appropriate values

$$a_x \;=\; 0.160 \text{ mm}$$

$$a_\phi = [C_\tau\, AL\, P_x + (C_\tau\, A - m\, f^2)\, M_y]/\Delta(f^2) \tag{4}$$

Substituting appropriate values

$$a_\phi \;=\; 0.032 \times 10^{-3} \text{ rad}$$

Thus maximum amplitude of vibration at centre of the bearings

$$= \; a_x + a_\phi \;\text{(H-L)} \tag{5}$$

$$= \; 0.160 + 0.032 \times (5.70 - 2.22)$$

$$= \; 0.27 \text{ mm} < 0.60/2, \text{ i.e., } 0.30 \text{ mm (using F.S.} = 2)$$

However, two broken blades on the same axis is a remote possibility and a safety factor of about 4.5 (=0.60/0.135) will be available under one broken blade condition.

Also under normal running condition, the unbalanced force is 5.2 kN so that the amplitude of vibration would be 0.02 mm (=0.27 × 5.2/72.5) by proportion which is well within the permissible limit of 0.12 mm.

Natural Frequency from Sweep Through Test

A sweep-through test was conducted to check the dominant horizontal mode frequency of the foundation (by extrapolation from the partial resonance curve) and make necessary modifications in the computed vibration amplitudes. The test was performed by switching off the machine and recording the velocity response in the horizontal direction at the top of foundation block at gradually decreasing speeds. The test was repeated for checking reproducibility of observations. Instantaneous measurements were possible due to the heavy interia of the system on account of large mass of the rotating parts including the flywheel so that the speed reduced very gradually on switching off the motors.

To construct the resonance curve as shown in Fig. 3, the response was first obtained for a constant dynamic force at the full speed of 600 rpm, by increasing the observed vibration amplitudes and multiplying them by the square of the ratio of the operating to the recorded speed of the machine. The modified displacement values, X_m thus obtained from recorded values, X are plotted in Fig. 3. The curve in this figure, when extended to the left to zero speed yields 'static amplitude' of 80 μm. Also it is clear from the figure that the resonance peak is not obtained till the operating speed of 600 rpm.

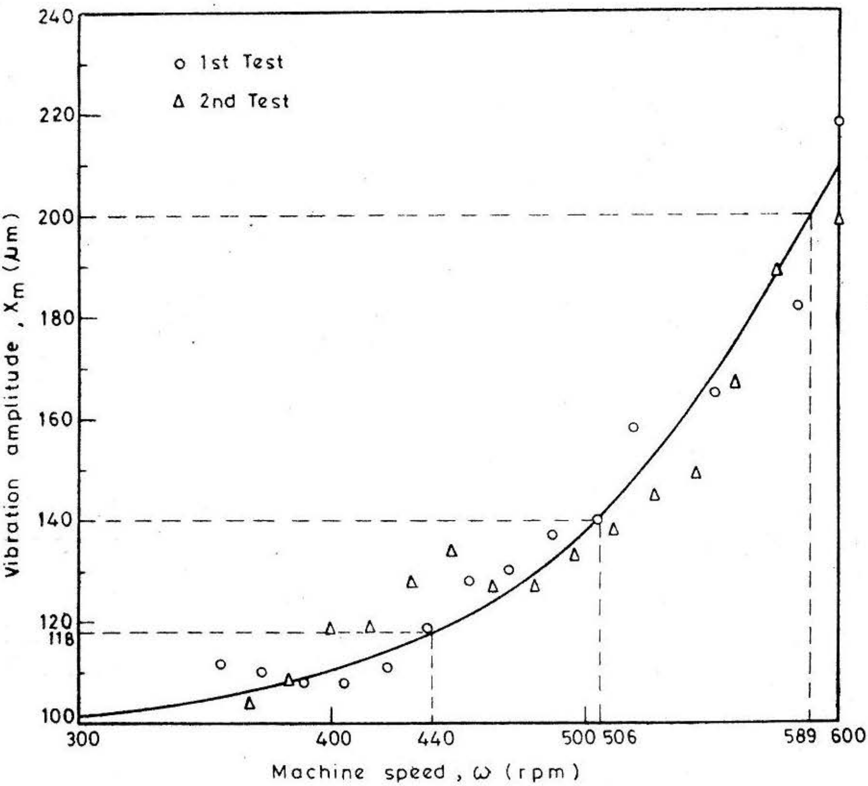


FIGURE 3 Resonance curve of the Second Cane Cutter Foundation from Sweep Through Tests

It would be fairly reasonable to assume that the first mode of horizontal vibration will contribute insignificantly to the response of the foundation for speeds more than approximately 425 rpm due to its relatively low and far removed natural frequency of about 278 cpm, thus giving the response in this range by the single-degree of freedom system equation

$$\mu = [(1-\eta^2)^2 + (2\eta\zeta)^2]^{0.5}$$

$$= \left[\left(1 - \frac{w^2}{f^2}\right)^2 + \left(2\ \frac{w\ \zeta}{f}\right)^2\right]^{0.5} \tag{6}$$

where μ is the dynamic amplification factor obtained by dividing the modified vibration displacement, X_m by its initial or static value of 80 μm; η is the ratio of machine speed, w during the sweep-through test to natural frequency of vibration of the foundation, f; and ζ is the fraction of critical damping.

Since X_m and hence μ are known for a particular value of w from Fig. 3, the only unknowns in equation (6) are f and ζ which can be evaluated by any curve fitting technique (Bansal, 1972). However, large error in the computed damping can result when equation (6) is used in the non-resonant range of η, as in the present case. It is therefore considered appropriate to assume an accepted damping value of 8% of critical (Major, 1980). Hence $\zeta = 0.08$ has been adopted and equation (6) solved for the following three points on the resonance curve of Fig. 3.

(*i*) $X_m = 118 \mu m$ $\mu = 1.475$ $w = 440$ rpm

(*ii*) $X_m = 140 \mu m$ $\mu = 1.750$ $w = 506$ rpm

(*iii*) $X_m = 200\ \mu m$ $\mu = 2.500$ $w = 589$ rpm

For the first point equation (6) yields the natural frequencies, f of the foundation block as-

$f_1 = 343$ cpm and $f_2 = 768$ cpm

The first natural frequency, f_1 is too low compared to be machine operating speed of 600 rpm beyond which the resonance peak is eminent in Fig. 3. Hence it has been omitted and f_2 considered to be the resonant or natural frequency of vibration. Values of f_2 obtained from the second and third points are 764 cpm and 748 cpm respectively. All the three values are quite close though obtained from assumed damping and for machine speeds spread over considerable frequency range of 440 to 589 rpm ($\eta = 0.58$ to 0.78). Hence the natural frequency of vibration in the second mode can be quite accurately represented by the average value obtained from the three points.

$f_2 = (768 + 764 + 748)/3 = 760$ cpm.

The experimental value of 760 cpm is very close to the earlier value of 749 cpm obtained theoretically. The corresponding dynamic amplification factors are 2.233 and 2.315 respectively for operating speed of 570 rpm assuming 30 rpm slip at full load, so that the computed vibration amplitude will increase in the ratio 2.233 to 2.315. Corrected theoretical vibration amplitude for two broken blade condition $= 0.27 \times 2.233/2.315 = 0.26\text{mm} < 0.60$ mm.

For normal running condition the corrected amplitude of vibration $= 0.02 \times 0.965 = 0.019\text{mm} < 0.12\text{mm}$

Analysis For Vertical Vibrations

The natural frequency of vertical vibration f_{ny} is given by

$$f_{ny}^2 = \left(\frac{C_u A}{m}\right) = 3492\ s^{-2} \tag{7}$$

f_{ny} = 59.08 rad/s = 564 cpm

Corrected f_{ny} is obtained by modifying it in the ratio of experimental to theoretical value of the second horizontal mode frequency.

Corrected f_{ny} = 564 × (655/749) = 493 cpm

Corrected C_u = 3000 × $(493/654)^2$ = 23,000 kN/m²

Frequency ratio = w/f_{ny} = 570/493 = 1.156

Dynamic amplification, $\mu = [\{1\text{-}(1.156)^2\}^2 + \{2\times1.156\times0.08\}^{2}\text{-}0.5] = 2.722$
Maximum dynamic force with two broken blades

$P_y = P_x = 72.5$ kN

Static deflection produced by P_y

Δstatic = P_y/C_uA

$= 72.5 \times 10^3 /(23000\times38.4) = 0.082$ mm

Vibration amplitude with two broken blades

$= 2.722 \times 0.082 = 0.224$ mm < 0.60 mm

Under normal running P_y = 5.2 kN so that the amplitude of vibration = 0.224 × 5.2/72.5 = 0.016 mm < 0.12 mm.

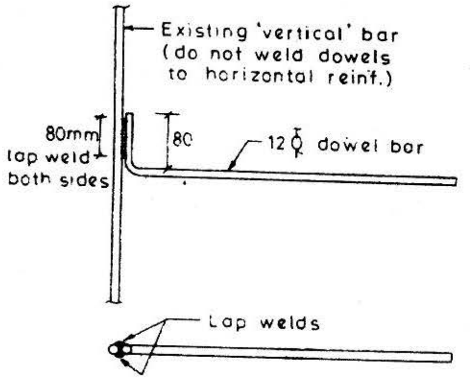
Construction Details

The addition of the mass to the existing foundation was carried using M-150 (1:2:4) concrete and tor steel bars of (guaranteed Fe - 415 grade) 12 mm diameter placed in all directions in the new concrete at a spacing of 200 mm c/c. The continuous bars in plan forming closed rings were provided laps of 63 diameters, that is, 750 mm for the 12 ϕ bars. The dowel bars of 12 mm ϕ tor steel at 300 mm spacing were placed in both directions to connect the old and new reinforcement. The dowel bars were welded to the old vertical bars as shown in Fig. 4.

The surface of old concrete was roughened by chipping and then cleaned thoroughly by hard wire brushes and compressed air before placing the reinforcement. The old concrete was also thoroughly cleaned and wetted by using water jets before pouring the fresh concrete. The concrete was poured in a single operation to avoid cold joints.

Performance

The observations of acceleration at different points on the pedestals and the base raft were taken soon after the strengthening measures in



Notes:

1. All dimensions are in mm.
2. All bars are 12 mm ϕ bars.
3. Spacing of main reinf. is 200 & dowels 300 mm c/c
4. All around bars in plan must be made continuous by providing lap length of 750 mm.
5. Concrete used should be of M-150 grade.
6. Old concrete surface should be meticulously prepared as suggested in the report.
7. Provide extra inclined bars @ 300 c/c in cantilever projn.
8. Provide cover of 25 mm
9. Entire concreting should be done in a single operation.

FIGURE 4 LAP Welds for Dowel Bars

November 1987 and later in April 1988 and July 1988. These observations are summarized in Tables 1 and 2. It is seen from these tables that the vibration amplitudes have reduced to almost half after the remedial measures in both the directions at the top of block A which has much larger amplitudes than block B.

Comparison with Thoery

The accelerations of the foundation block excited by removing two blades in the same line were also recorded on a direct ink writing oscillograph to study the waveform of the vibrations. The record showed vibrations of twice the frequency of the machine speed, that is 20 cps. Displacement amplitudes have therefore been computed from the accelerations using the observed frequency value of 20 Hz or 125.6 radians per second.

$$\text{Displacement peak} = \text{acceleration}/w^2 \tag{8}$$

where

$w = 125.6$ rad/s

Thus for peak acceleration values of 0.50 g recorded in each direction (Tables 1 and 2), the displacement peak would be $0.50 \times 9800/(125.6)^2 = 0.31$ mm. This is in close agreement with the theoretically computed values of 0.44 mm and 0.23 mm in the horizontal and vertical directions respectively.

Under the normal running of the cutter with full cane load, the measured peak accelerations are 0.34 g in the horizontal direction and 0.50 g vertically. However, the frequency content of the accelerogram is somewhat irregular and much higher than 20 Hz. It varies between 50 Hz to 80 Hz or 314 to 500 radians per second. Using an average va!ue of say 400 radians per second, the displacement amplitudes are obtained as 0.021 mm and 0.030 mm which lie very close to the theoretical values of 0.032 mm and 0.016 mm respectively.

Discussion

Two broken blades on the same axis is the most severe condition considered for the design of the foundation. The vibrations thus produced are felt strongly in the office building about 70 m away.

The measured horizontal peak acceleration after the strengthening of the cracked foundation block was 0.50 g (0.90 g before the remedial measures), while dominant frequency content of the recorded accelerations was 20 cps, yielding peak single displacement amplitude as 0.31 mm. This is close to the computed value of 0.44 mm.

Modifications done by way of extra concreting caused almost no change in the horizontal natural freuqncy (from 754 cpm to 749 cpm for C_u of 30,000 kN/m^3.

Increase in the driving HP from 450 to 700 by installation of a new 250 HP motor at the other end of the shaft has made practically no difference in the acceleration amplitudes (Tables 1 and 2).

Acceleration amplitudes at the top of the foundation block reduced to almost half in both horizontal and vertical directions after the remedial measures.

Back analysis carried out for horizontal vibrations showed a decrease in the horizontal natural frequency from 749 cpm to 655 cpm with consequent increase in the vibration amplitudes from 0.27 mm to 0.44 mm. It also helped in establishing the dynamic elastic coefficients of the soil. With the help of the experimentally obtained elastic constants of the subgrade the amplitudes of vibration could be more accurately computed as seen from the closeness between the theoretical and measured responses.

Conclusions

On the basis of the theoretical analysis of the cane-cutter foundation and its performance under various conditions, the following conclusions are drawn :

(1) Two broken blades along the same line give the more adverse design condition for the foundation, although the acceleration amplitudes for both the conditions are nearly same.

(2) Acceleration amplitudes at the top of the b'ock reduced to almost

half after the remedial measures, while changing little at the base of the block.

(3) Installation of an additional 250 HP motor resulted in 55% increase in the driving capacity but caused very little change in the acceleration responses.

(4) Back analysis from the sweep-through test helped in more accurate predictions of the response as seen from the closeness to the observed values in both the directions and for both the operating conditions.

(5) The cracked massive foundation of more than 3000 kN has been effectively repaired by additional concreting without the use of special adhesives, cements or any admixtures.

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