Analytical and Experimental Investigation of the Effects of Concrete Removal Operations on Adjacent Concrete That is to Remain

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16. Abstract

This report contains both analytical and experimental work, as well as mathematical work on concrete bridge, located on Route 89 in Vermont. The bridge was renovated by replacing the deck. The experimental work included monitoring the effect of the Hoe-Ram operation on the remaining concrete, by placing strain gages at different places on the deck, abutments and piers. The gages were connected to strain monitoring equipment, which was connected to a lap top computer to record the strain gage readings. Concrete samples were taken locations adjacent to the points, where the Hoe-Ram operated. They were tested to find it that concrete was affected by the operation. The analytical work included the simulation of the Hoe-Ram operation as static and dynamic load. The concrete elements were modeled in a finite element configuration and special software was used to do the analysis. The software was ANSYS. The analysis showed the contours of stresses in the area adjacent to the points of the Hoe-Ram operation. Both analytical and experimental results were consistent with each other, having some acceptable margin of difference. The mathematical work included the use of the wave equation to predict the effect of the Hoe-Ram on the deck by using differential equations, then using special mathematical software to solve those equations, after applying the boundary conditions.

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TABLE OF CONTENTS

NETC PROJECT No. 99-6
FINAL REPORT

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF CONCRETE REMOVAL ON ADJACENT CONCRETE THAT IS TO REMAIN

PROJECT DESCRIPTION

The project is the southbound bridge on route 89 in Vermont. The research work consisted of two parts, mainly experimental research work and analytical as well as mathematical research work to study the effect of using heavy demolition equipment, such as Hoe-Ram effect on the concrete to remain.

The experimental work included the installation of several strain gages on the deck, the abutments and a pier. Connecting all the gages by wires to strain measurement equipment. The equipment are connected to a lap top computer to convert the electric signals to digital readings, stored on the hard disk drive of the computer in the form of tables. The electric signals are converted to digital signals through the software provided by the equipment manufacturer National Instrument. The digital readings represent the concrete strain, at the strain gages location, due to the operation of the Hoe-Ram. Furthermore, several samples were taken from the site to test them in the lab to determine the concrete ultimate strength and the effect of the Hoe-Ram operation on the bond stress of the reinforcing bars of the remaining concrete.

The analytical research work included the static and dynamic analysis of the Hoe-Ram force effect on the slab and abutment walls, and the indirect effect of the force on the piers. ANSYS software program was used in the analysis for both static and dynamic analysis. It also used the energy method to justify the equivalent load assumption from converting the Hoe-Ram energy of one stroke to strain energy in the structure.

The mathematical analysis modeled the effect of the force on the structural slab using the wave equation principles. Special mathematical software was used to solve the differential equations obtained from the mathematical model to obtain the displacements at several sets of points on the slab. Those displacements were then plugged in the ANSYS program to determine the stresses at the point of load application as well as few adjacent points.

A comparison was made between the results obtained from the experimental, analytical and mathematical models.

A. EXPERIMENTAL WORK

A1. Location of Gages and Hoe-Ram Operation

The strain gages were placed on the deck, the pier, the north and south abutments. They were placed in such a way to measure the concrete strains in two directions (vertical and transverse). The Hoe-Ram in its operation punched holes in the deck, the closest any hole came to the gage was about 8 inches center to center.

A2. Data Acquisition by the Computer

Data acquired by the computer from the strain reading equipment were used to compare the experimental and analytical results. The equipment were capable of delivering 63000 readings per minute for each gage. It was switched on for an interval of time ranging between 10-25 minutes, while the Hoe-Ram was in operation. This meant that more than one million readings were taken for each gage.

A3. Data Plotting and Interpretation

In order to avoid printing countless number of pages of data, it was decided to plot the data for each gage readings. The vertical scale was the strain of concrete indicated by the gage reading in micro strains and the horizontal scale was the time readings of the equipment. The time scale was compacted to fit in one sheet.

The unfortunate event was the noise in the equipment readings because there was a broadcasting station next to the project, which generated electronic interference. We tested the equipment before starting the project. It was quite accurate in its readings. For example we ran the following test at Uconn's Lab: We attached two gages to a concrete cylinder sample, then we connected the gages to the strain reading equipment. When the concrete cylinder was about to be crushed in the test the strain readings of the gages were 0.003000 or 3000 micro strain. We repeated the same experiment on another concrete cylinder in the lab and achieved same result. However, when we used the equipment in the project, the noise interference continuously disturbed the readings. In order to neutralize the effect of the noise we decided to add the readings and plot the summation as well as the individual readings, so that the negative noise will cancel the positive noise. Accordingly such plotting could be considered relatively free of the noise effect. Gage V10 and V13 recorded such readings at the deck between ±1000 micro strain, which gives concrete stress around ±1300 psi. Such readings were comparable to the readings from static and dynamic load analysis at a distance 6-12 inches from the center point of load application. The fluctuation of the graph and its deviation from ± 1000 is attributed to the dynamic effect of the Hoe-Ram as well as to the noise. This part will be discussed in details at the static and dynamic analysis. At the north abutment three gages T3, T4 and V6 failed under extremely high strains. It could be that the falling debris from the Hoe-Ram operation hit the wires connecting the gages to the equipment, causing tension in the wires. This tension pulled the resistance of the gage beyond the limit causing its destruction. It is also possible that there was really such high strain in the concrete causing the failure of the gages. But the fact that such event did not occur at the south abutment and gage V4, which was closer to the Hoe-Ram operation than gage V6, did not fail proves that most likely it was the falling debris caused the gage sudden destruction. Furthermore, the static and dynamic analysis of the wall, which will be discussed later, did not show any significant stress at such distance. Therefore, it can be concluded that the three gages failed because of the falling debris.

Interesting enough gages V18 and V19 did not show anything other than the noise and some vibration effect, because they were placed on the solid foundation of the abutment. Contrary to that result was gages V15 and V16, which showed considerable strains because they were placed at the bottom of the columns between the pier and the top concrete beam, which supports the steel girders. Again gage T13, which was placed on the beam supporting the girders did not show any significant strain because the deck was moving the whole beam back and forth, instead of bending it.

A4. Lab Testing of Concrete Samples

The lab testing purpose was to determine the ultimate strength of the concrete and to find if the Hoe-Ram demolition could have any effect on the bonding stress of the reinforcing bars in the concrete to remain.

Two concrete blocks were taken from the deck. Block A was taken from a distance of 2 feet from the edge of the demolition and block B was taken from a distance of 5 feet from that edge. Both blocks were cut from the deck by the saw. At the lab the concrete around the bar was removed to expose a small stub from the bar to facilitate the testing. The reinforcing bars were deformed bars. The testing of the samples showed that the ultimate bond stress were 1268 and 1515 psi respectively. A slightly less in the block closer to the demolition, however, when compared to the bond stress given by the ACI code formulas, those stresses were a lot more than what the formula gave. Formula 1 gave 202 psi and formula 2 gave 506.7 psi. It can easily be concluded that the bond stress does not get affected at a distance of 2 feet from the edge of the demolition, unless the Hoe-Ram kept hammering on the bar, which they usually avoid to do.

B. ANALYTICAL WORK

B1. Static Analysis

The static part of the software ANSYS was used to analyze the slab and find the effect of the operating Hoe-Ram on the adjacent concrete. The Hoe-Ram was crushing the concrete in its hammering, making a hole of its size in the slab. Because the Hoe-Ram bit diameter was 4 inch nominal and therefore the static load can be assumed to be the load, which crushes the concrete at a circular area of 4 inches in diameter. Since the lab test of the cylinder samples, taken from the deck had 4000 psi concrete strength, therefore the crushing force was $(4)^2 (4000) (\pi/4) \approx 50000$#. The slab was modeled as 4x4 inches elements with the proper boundary conditions and a load of 50000# was spread over the element.

B1a. Static Load on 7.5 inch thick deck

To find the location, which will give the maximum stresses, the 50000# was placed at different distances from the edge. It was placed at a distances of 44 inch from the edge, then changed to different distances until it was found that a distance of 36 inch from the edge gives maximum stresses. However the difference in stresses between those locations were insignificant. It will be shown later in Fig.1 that the stress was a function of the deck thickness rather than the span or the location of the Hoe-Ram.

The load was placed at three different locations on the deck, mainly at 32, 36 and 44 inches from the edge. The stresses in the X, Y and XY direction were compared for the three load locations and found to have maximum value when the load was placed at 36 inches.

The stresses decreased in the elements of the slab, which were farther away from the point of load application. However, all stresses were less than the crushing stress of the concrete, except that in the Z direction (The direction which was perpendicular to the deck). Therefore, It can be said that for point load on a two way thick slab the maximum stresses are slightly influenced by the span or the location of the load.

It is clear from the stress contours that higher stresses are confined to an area of 12 inches diameter around the Hoe-Ram load application point, as shown in Fig.1. This can be seen clearly after knowing that each square in the mesh represents 4 x 4 inches, which is the size of the mesh. This analysis was confirmed by the fact that there was no crack developed around the holes created by the Hoe-Ram hammering, It is also confirmed by the strain gage readings. The closest the Hoe-Ram operation came to the strain gage was 6 inches from the edge of the hole. The strain in gage V10 showed about 1000 micro strain. Such strain is associated with concrete stress equal to 4000 psi divided by 3, which equals 1333 psi. The concrete ultimate stress was 4000 psi and the ultimate strain is 0.003 or 3000 micro strain.

B1b. Static load on 3.5, 5.5, 9.5 and 11.5 inch deck

The 50000# load was placed on decks with different thickness. The load was kept always at the same 36 inches distance from the edge and the boundary conditions were kept the same. The analysis showed that decks with thickness larger than 7.5 inches their stress contours were inversely proportionate to the thickness.

When the deck thickness was reduced to 5.5 and 3.5 inches the stresses were higher respectively, as shown in Fig.1. In the 3.5 inches deck the stresses were more than the ultimate strength of the concrete, which meant that the slab would be shattered.

B1c. Energy calculations

ANSYS software calculates the strain energy in the analyzed structure. It evaluates the energy using an equation embedded in the software. Each element in the mesh has its own value of the strain energy. Summing the total strain energy gave comparable value to that given by the Hoe-Ram in one blow, as given by the manufacturer's catalog. Furthermore, a manual calculation was made, using stress contours and stress and strain in the deck. The strain energy was again close to that of the Hoe-Ram, as given by the manufacturer's catalog. This shows that using an equivalent 50000# static load has created strain energy in the structure equivalent to that given by one blow of the Hoe-Ram. It proves that the assumption was correct.

B1d. Static load on north abutment wall

Because the wall was thick wall of 1.5 feet thickness, it was necessary to analyze it as 3-D structure using 3 dimensional elements. The element’s size was chosen to be 6 x 6 x 6 inches. Since the wall is 1.5 feet thick the Hoe-Ram cannot be effective if used perpendicular to the surface of the wall, unless it is used very close to the edge. From the analysis of the 7.5 inches deck it became clear that it would just punch a hole in it. Therefore the Hoe-Ram was used to hammer at the top of the wall in a direction inclined by 60 degrees to the bridge deck. This way the force, which will drill a hole parallel to the main reinforcement, and it will have a horizontal component kicking sideways, creating tension in the concrete. Such tension will not be resisted by the main reinforcement, located at the faces of the wall. This way the wall can be demolished by the Hoe-Ram. The finite element analysis of the wall, considering the static load of the Hoe-Ram to be 50000#, showed that the tension stress created by the horizontal component could only locally exceed the concrete ultimate tension stress in the z direction.

The ultimate concrete tension stress is considered to be 10% of the crushing stress. The magnified wall stresses in 3-D, indicated that excessive tension stress occupies an area between 6 and 10 inches.

One inconsistency arose between the analytical and the experimental results for the wall in the north abutment. The experimental results showed that gages marked T3, T4 and V6 were reading very high strains in the order of 60000 micro strains or 0.06. Such high strain indicated that the concrete has been crushed at a distance of 4 to 5 feet from the spot, where the Hoe-Ram was operating. Such event was not backed by personal observation or by the analytical method. Furthermore, such thing was not observed in the southern abutment. Therefore, the only logical explanation could be that the debris falling from the top of the wall has hit the wires connecting the strain gage with the equipment, created an excessive pull on the gage resistance, thus busting the gage and showing such an excessive strain in the acquired data.

B2. Dynamic Analysis

ANSYS software was used again to analyze the structure dynamically, using the finite elements. Since the Hoe-Ram has several frequencies ranging from 470 to 1000 Blow Per Minute (BPM), it was decided that several values of frequency should be used to find its maximum effect. The dynamic load was used as a series of triangular load. The number of triangles should be compatible with each frequency. The dynamic load was used on the 7.5 inches deck, then on a 6.5 inches deck, in response to the chairman of the technical committee's request.

B2a. Deck 7.5 inches thick

The manufacturer catalog shows that the Hoe-Ram model H100 operates with a frequency ranging between 470 and 1000 Blows Per Minute (BPM). Accordingly the dynamic load of 50000# should be applied at Variable values between a band of time for that frequency. It starts with zero value just when it hits the concrete surface and becomes maximum 50000# when it penetrates to the maximum depth, then it gets back to zero, when it totally disengage from the deck. The lowest frequency is 470 BPM, which is equivalent to 49.2 rad/sec. Other frequencies are higher than that. In the meantime the 1st mode frequency of the deck is much lower than the operating dynamic load frequency of the Hoe-Ram. Even higher modes frequency of the deck, such as the 10th mode, which is 10.22 rad/sec and the 20th mode, which is 16.412 rad/sec are less than the lowest Hoe-Ram frequency. Therefore it is obvious that the lowest Hoe-Ram frequency will have the biggest effect on the slab, other frequencies will have less effect. The magnitude of their effect depends on how close they are to one of the deck natural frequencies. Thus the 470 BPM was expected to produce the highest stresses. It showed that the stresses in the Y direction S_y has maximum value of 3181 psi right under the Hoe-Ram bit, where it punched the hole in the slab. The stress S_y of 1767 psi spreads to an area less than 3 feet long and 1.5 foot wide. Stresses in the X direction are even less than that. The maximum deflection was 0.15 inches. All other frequencies produced less stresses in both X and Y directions from those produced by the 470 BPM. The deflection was also smaller. For example at 1000 BPM it produced deflection of 0.05 inches under the load and stress as low as 86 psi in the Y direction and as low as 78 psi in the X direction. These results were quite compatible with what was seen visually. No cracks were noticed around the holes, which meant no overstressed areas were created other than the area of the hole. The slab was not shattered even though the vibration was quite high.

It is interesting to notice that the maximum stress, due to 50000# load applied dynamically, was 1.8 times the maximum stress produced by the same load, when applied statically Theoretically the ratio could go as high as 2.0 when the frequency of the structure and the frequency of the dynamic load are very close and there is no damping. However it seldom exceeds 1.5. In our dynamic analysis the internal structural damping, as well as other forms of damping were assumed to be zero. That is why sometimes the ratio was as high as 1.8.

B2b. Deck 6.5 inches thick

When the 50000# load was applied dynamically to a 6.5 inch slab, at a frequency of 470 BPM, the stress not only exceeds the crushing stress under the Hoe-Ram bit, but it also spreads to an area of 1.0 x 0.75 feet, which has stress of 4441 psi. There is also an area of 3 x 1.5 feet, which has significantly high stress of 3172 psi. It means that the slab could be shattered by the Hoe-Ram if it is 6.5 inches thick.

B2c. North abutment wall

Because the wall is thick wall, therefore it was analyzed as 3-D mesh. Each element of the mesh was 6 x 6 x 6 inches. The mode of natural frequency of the wall was 58.31 read/sec, which is equal to 556.8 cycles per minute. The deflection of the wall in the first mode was very small. The analysis actually gave the highest stresses in the x direction, when the load has a kicking horizontal component perpendicular to the wall. The same load of 50000# was applied inclined 60 degrees to the horizontal with a frequency of 600 BPM. The results showed that the maximum tension stress in the Z direction S_z was 173.7 psi. This stress is less than the stress, which can crack the concrete in tension, however, when the load was applied with 542 BPM it produced larger tension stress of 309.3. This stress is still less than 400 psi (10% of f_c = 4000 psi). The deflection of the wall in the Z direction had maximum value of 0.011 inch.

The results of this analysis confirmed that the failure of the gages T3 and T4 placed on the north abutment wall was not due to excessive stress, but rather due to the falling debris, which destroyed the gages.

C. MATHEMATICAL ANALYSIS USING WAVE EQUATION

C1. Vibration of the steel Girder

The differential equation of a vibrating clamped beam was derived (The deck is supported by 5 continuous deep girders). The girder is loaded with a load, which was function of the time and distance from origin. The general solution of the differential equation is obtained by applying the boundary conditions. Although the effect of the Hoe-Ram dynamic force is negligible on the deep girders, which has depth varies between 5 and 7 feet, however the vibration of the beam may have its effect on the deck, since they are integrated together. The force of the Hoe-Ram was assumed to act on different points along the girder. The force assumed to be distributed on a distance of ± 0.05m from the center of the force (since the Hoe-Ram has 4 inches diameter bit) acting with the frequency given by the manufacturer's catalog. The deflection of the beam under the Hoe-Ram load had maximum value of about 3.5 cm, which looks kind of excessive value. Such excessive value could be attributed to the fact that the moment of inertia of the girder was calculated just for the steel girder, while in reality it is a composite beam with the 7.5 inches thick concrete deck acting as the wings of a T beam. Such T beam will have moment of inertia three times the steel girder alone. In such case the deflection of the girder will be about 1.1 cm instead of 3.5 cm. Other source of discrepancy could come from the mathematical modeling, which may differ from the structural modeling used by ANSYS software.

C2. Vibration of a plate

A mathematical introduction demonstrated the elastic waves in solid media, in which stress tensors were components of the equations. Those equations were used in the analysis of the vibration in concrete plate. The initial and the boundary conditions from the previous sections were used. The derivation arrived to an equation, which is hard to find its analytical solution, given the set of initial and boundary conditions, so some simplification was introduced to get an analytical solution by assuming the four sides of the plate were simply supported. Using Fourier series and coefficients obtained previously and applying the initial and boundary conditions a solution for the rectangular plate was obtained in an equation contained two series and double integrals. Such equation was solved for different time intervals, using a special mathematical software program.

The load was assumed at different position each time and the time t started with 0.064 second and increased by that much for each step in time i.e. 0.064, 0.128, 0.192, 0,256 and 0.320 second. The displacement of the plate was found numerically for at least 4 points, but most of the time for 6 points. Each point is about one foot from the point of load application. Three sets of deflection tables were given, one for 7.5 inches thick deck, a second one for 5.5 inches deck and a third one for 3.5 inches deck. Those deflections are function of the load of the Hoe-Ram, the time and position of the point, which the deflection is calculated at, and the position of point of load application.

C3. Stresses due to deflection of the points given by the wave equation

Those deflections obtained mathematically were plugged in the ANSYS finite elements program to obtain the stresses in the plate. In this case the deck was shown supported continuously on the girders. The stress contours in the X and Y directions were obtained for each time interval. Decks of 7.5, 5.5 and 3.5 inch thick were used. The results showed that at certain time intervals the stresses in the plate become higher for some points than the ones given by ANSYS finite elements program. However, magnifying the overstressed areas showed that such overstressing occurred only at a very small area. The stress of 6400 psi occupied an area of 4 x 4 inches and the stress of 5000 psi occupied an area of 8x8.5 inches. The rest of the area is stressed below the ultimate strength of the concrete. In general, these results agree with the static and dynamic analysis of the deck, using ANSYS finite elements, in the sense that the stresses become progressively higher when the plate thickness decreases. The excessive stress for certain points at certain times intervals, compared to what was given by ANSYS, could be attributed to the fact that the boundary conditions were changed to simply supported plate instead of a plate continuous at one edge, while in ANSYS finite elements program the plate was continuous on the girder. As it was mentioned before, the boundary conditions were changed to simply supported edges in order to obtain an explicit solution for the differential equation. Furthermore, the numerical solution method used by the mathematical program could be different from that used by ANSYS at certain time intervals, as well as other mathematical discrepancies.

In any case, any extremely high stresses, though occur in small areas, do not agree with the physical facts in the field, which just showed holes in the deck due to the Hoe-Ram hammering, rather than massive collapse of the slab. Other points of high stresses occurred in the thin slabs 5.5 and 3.5 inches thick.

The dynamic analysis of the 6.5 inches deck, using ANSYS program, showed the following excessive stresses: An area 4 x 4 inches has 5153 psi stress, an area 8 x 8.5 inches has 4008 psi stress. Thus the dynamic analysis of 6.5 inches deck showed that it is inadequate. The 7.5 inches deck is quite adequate for the operation of a 4 inches diameter bit Hoe-Ram, when the intention is to demolish one part of the deck and leave the adjacent part intact. The influence of the Hoe-Ram on the adjacent part in the 7.5 inches deck is minimal, while any other thickness, which is less than 7.5 inches could create problems.

D. THE EFFECT OF OTHER METHODS OF DEMOLITION

D1. Hydro-demolition method

The basic parameters of this method are: Water pressure as high as 241 MPa (35000 psi) is applied through a nozzle. The rate of flow of the water equals 120 liter /min (32 gal/min). Carriage speed equals 400 mm/sec (1.31 ft/sec). Time for one pass equals 5.4 sec/pass. Length of one pass equals 1.31 x 5.4 = 7.074 ft along the width of the bridge, which is equal to the width of the carriage. Number of passes per one advanced increment equals 1-4 passes. Each advance is about 30 mm (1.18 inches). One cycle is formed by one pass forward and one pass back. Therefore one cycle takes 5.4 x 2 = 10.8 second.

Therefore the frequency is 2 x π / 10.8 = 0.582 rad/sec

In order to find the force of the water jet on the concrete, the following calculation is needed:

$$h_v = \frac{v^2}{g} = \frac{p}{\rho g} \qquad (1)$$

Where:

h_v is the velocity head
p is the pressure of water
ρ is the density of the water
v is the velocity of the water jet in m/sec

$$v = \sqrt{\frac{p}{\rho}} \tag{2}$$

$$\mathbf{Q = v\ A} = \sqrt{\frac{p}{\rho}}\ \mathbf{A} \tag{3}$$

Where:
Q is the discharge in m^3/sec
A is the area of the orifice in m^2

Q = 120/(1000x60) = 0.002 m^3/sec

Applying this discharge in Eq.3 gives the area A of the nozzle

$$0.002 = \sqrt{\frac{241000000}{1000}}A$$

A = 4.082 x 10^{-6} m^2 = 0.04 cm^2 = 0.0062 in^2

Force of water jet on the concrete deck = 35000 x 0.0062 = 217 #

Such dynamic force has no significant effect on the stresses in the deck, when compared to the 50000# dynamic force of the Hoe-Ram. Its effect is only locally, which is to brake the concrete bonding.

D2. Roto-milling method

This method can create tension or compression at the top surface of the concrete deck, due to the shearing force in the concrete surface due to the milling. Because the force crated by the milling is parallel to the surface of the deck, therefore it cannot have the effect of the Hoe-Ram force, which is perpendicular to the surface of the deck.

E. CONCLUSIONS

The experimental procedure of using strain gages and strain measuring equipment showed that the effect of the Hoe-Ram, which has 4 inches diameter bit, is very limited on the adjacent parts of the concrete deck, when the thickness is 7.5 inches or more. The strain measurement at gage V10 was about 1000 micro strain. It was located at a distance of 6 inches from the edge of the hole crated by the Hoe-Ram. Such strain is compatible with the 1330 psi in the static mode. This stress compared favorably with the stress of 1304 psi in the Y direction and 1120 psi in the X direction at a distance of 6 inches from the edge of the Hoe-Ram bit. The dynamic analysis showed that the dynamic effect could be as high as 1.8 times the static load effect because internal damping was considered to equal zero.

Slabs thicker than 7.5 inches are quite safe to operate on with the 4 inches Hoe-Ram bit. However, when the slab thickness decreases the effect on the adjacent parts increases rapidly, as it is shown in Fig.1, and it could shatter the slab, while for the 7.5 inches slab the Hoe-Ram hammering creates only a hole in the slab. The bonding stress of the reinforcing bars does not get affected unless the Hoe-Ram happened to hammer on a reinforcing bar. Even then the testing of a sample showed that if such thing takes place, it diminishes at a distance of 2 feet from the point of the Hoe-Ram application.

Thick walls behave like thick slab, the Hoe-Ram can only create a hole rather than large cracks, when it is directed perpendicular to the wall, however, when it operates at the top of the wall and inclined to the horizontal plane, or perpendicular to the wall at its edge, then it starts chipping the wall at a local area. Thin walls behave like thin slabs. They could be shattered under the Hoe-Ram hammering. The energy calculation showed that the energy of one stroke of the Hoe-Ram is equal to the strain energy stored in the slab, which confirms that the 4 inches diameter Hoe-Ram impact load is equivalent to 50000# static load.

Although there was no concrete beam in this project, however, it could be said that concrete beams are expected to behave like a thick slab if the hammering was perpendicular to the axis of the beam.

The wave equation solution gave larger stresses than those given by ANSYS software. However, they were consistent with those results in a sense that they increased with the decrease of the thickness of the slab. Furthermore those high stresses were confined to very small areas, as demonstrated by the magnified figures.

Other methods such as hydro demolition and roto-milling had much smaller influence on the remaining structures than the influence of the Hoe-Ram.

F. TECHNOLOGY TRANSFER

This research arrives to the following technical points, which could be considered technology transfer:

1- The equivalent static load of the 4 inches diameter Hoe-Ram bit impact is 50000#.

2- An equivalent static load for smaller size Hoe-Ram can be derived as proportionate to the ratio of the energy delivered by other size to that delivered by the 4 inches Hoe-Ram.
3- The dynamic effect of the Hoe-Ram load could be as high as 1.8 times the static load.
4- Operating a 4 inches diameter Hoe-Ram perpendicular to 7.5 inches deck creates only a hole in the deck and its effect diminishes about 2 feet from the operation point, as shown in Fig.1. The effect becomes larger at thinner slabs to the extent that it could shatter the slab or creates long cracks.
5- When operating a 4 inches diameter Hoe-Ram perpendicular to the surface of the thick wall or perpendicular to the axis of a beam, its effect will be just creating a hole like it does in a 7.5 inches slab when the Hoe-Ram is at least 2 feet from the edge, however, when it is close to the edge it chips off the concrete in an area of influence of 1 ft from the point of operation
6- Because the manufacturer's catalog had a maximum diameter of 4 inches bit, the experimental and the analytical study were confined to criteria of that diameter. Any future equipment, which has larger diameter bit, its influence should not be extrapolated. However, for a smaller diameter the influence could be linearly interpolated in a way proportionate to their respective energy given by the manufacturer's catalog.
7- The location of the point of operation of the hoe-Ram bit does not have significant influence on the stresses in the 7.5 inches thick slab or thicker. In other words the stress contours may not have more than 10% change in stresses, when the Hoe-Ram operates at mid span or closer to the support.

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