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Forensic Engineering Analysis of Dynamic Wheel Tire Impact Ejection of Manhole Covers

by Jon O. Jacobson, Ph.D., P.E. (NAFE 401F)
Michael Kravitz, P.E. (NAFE 451F)

Abstract

This paper will examine the effect of vehicle tires driving over a street hardware manhole cover that was not properly seated and resulted in the motion of the manhole cover which eventually either became unseated and moved along the roadway surface or failed and fell into the manhole. As a result of the open uncovered manhole, a vehicle tire struck the open manhole resulting in the driver losing control of the vehicle and crashing into a tree. Several of the passengers were injured and a law suit ensued. The issue of notice was the focal point of the case. The defendant's argument was that it had no notice of the defect and the plaintiff's argument was that the defendant had actual and constructive notice because the defect was caused by the roadway resurfacing project. Two examples will be presented showing how a manhole cover can be dislodged they are: 1) The dynamic expulsion from tire forces on the rocking manhole cover, and 2) The fracture of the manhole cover from local contact stresses from a misaligned adjusting riser frame installed during the repaving.

Keywords

Forensic Engineer, casting, manhole, notice, resurfacing, riser, street.

Events Leading to Trial

The roadway where the event took place was a moderately traveled road which was recently resurfaced with asphalt. The roadway was thirty-four feet wide with sidewalks on each side and was divided into approximately three eleven foot lanes. The center lane was used as a turning lane. The center of the manhole was located approximately nine feet from the curb and approximately two feet from the double yellow line dividing the driving lane from the turning lane. Generally, a vehicles left front and left rear tires would ride over the manhole cover. The roadway was straight for approximately one thousand feet with a speed limit of 30 MPH. The event occurred at approximately 4:30am during the summer. The roadway was sufficiently lighted but the driver of the vehicle did not see the open manhole. The roadway resurfacing was completed approx-

Jon O. Jacobson, Ph.D., P.E., 5220 Roosevelt Way N.E., Seattle, WA 98105
Michael Kravitz, P.E., 484 West 43rd Street, Suite 32s, New York, NY 10036

imately four months prior to the event but it was not known when this particular manhole frame casting was installed and/or adjusted relative to the start and finish of the resurfacing contract. It should be noted at this point that the manhole cover was never found and assumed by the owner (defendant) that it was stolen. However, no one looked inside the manhole to see if the manhole cover failed (fractured) and fell down into the manhole. The Plaintiffs began a law suit involving the contractor, for the resurfacing; the county/owner of the street hardware adjustment; and the driver/owner of the vehicle. There was a witness statement which indicated that the manhole cover started to "bang" when vehicles rode over it after the completion of the resurfacing project, and that on one occasion the neighbor had replaced the manhole cover after it had become dislodged from the casting. However, the neighbor had never informed the owner that the manhole cover became dislodged or repeatedly banged from the traffic passing over it. The plaintiff's theory at the outset of the case was that; a defective condition was created when defendant failed to properly install and adjust the manhole ring and cover; failed to properly place a correct manhole cover in the ring and casting; upon completion of the repaving of the street; failed to remove the sewer manhole cover; failed to clean and reinstall the proper street hardware; and failed to properly re-inspect the manhole cover, the adjustment ring, casting and failed to properly inspect the roadway on completion of the project. Also included in the complaint was improper inspection because the manhole cover was not mated properly to the casting as evidenced by the repeated banging; that there was no locking device between the manhole cover and the casting; the manhole cover and casting were improperly adjusted. The parties could not come to a settlement and so the case went to trial.

Case Analysis

The defendant's claimed that the replaced manhole cover was not the same nor was it in the same condition as the manhole cover at the time of the accident, and therefore would not allow an inspection of the manhole or replaced manhole cover or the adjustment riser. The Defendants also claimed that the manhole cover was stolen and therefore they did not have sufficient notice of the defective condition.

The plaintiff had recorded a video tape of vehicles driving over the replaced manhole cover wherein the replaced manhole cover was seen to be moving. A still image was taken from the video tape (shown below), however the writer was not convinced that the manhole cover motion shown was sufficient to cause the manhole cover to become dislodged from the casting. The writer inspected and measured the roadway and in the process took photographs of the manhole cover. It was then seen that the adjustment of the manhole for the resurfaced pavement was performed with an adjustable manhole riser. The adjustable manhole riser was not constructed as a uniform rigid heavy iron casting, but was a discontinuous circular ring with a turn-buckle to adjust the diameter of the riser to fit into the in-place casting. Attached to the metal ring was the seat where the manhole cover would rest. The seat for the manhole cover was not continuous. The theory of the adjustable riser was that when the turn buckle was expanded, the sides of the adjustment ring would be forced against the original metal casting; the turn-buckle would apply pressure to the inside of the in-place casting and the friction-bond between the two surfaces would be sufficient to hold the adjustable riser in place. The adjustable riser also relied on the seat that was attached to the adjustable riser ring to be in full contact with the manhole cover. However, there was no provision for the adjustable riser to be secured in the vertical direction. It was, more probably than not, estimated by the designer, that the manhole cover would provide sufficient weight along with friction to keep the adjustable riser from "riding" up along the side of the in-place casting, thus keeping the manhole cover in full contact with the adjustable riser seat. Looking at the photograph taken approximately four years later, the rim of the adjustable riser has a separation and height differential of approximately one-quarter inch. This would indicate that the adjustable riser seat for the manhole cover would be in the shape of a helix instead of a flat horizontal surface. The adjustable riser was re-adjusted after the event, and the manhole cover was replaced, the riser separation was probably greater at the time of the event. The writer, in making calculations estimated that the difference in height could have had a variance between one-eighth to three-quarter inches. It should also be noted that four years had elapsed between the event and the writer's inspection and that debris, more likely than not, had accumulated between the adjustable riser and the manhole cover which probably filtered down to the seat of the adjustable riser thereby eliminating the rocking of the manhole cover over time. It was the initial installation, estimated to be within the first year, of the adjustable riser whereby debris had as yet not accumulated, and where the created helix effect of the seat of the adjustable riser created the rocking and, either dislodging or cracking (failing) of the manhole cover, was of concern.

Calculations

It is estimated that the manhole cover would have been seated on a helix created by the adjustable riser. The range of the helix was estimated to be from 1/8" to 3/4". After the Manhole cover had been given the initial rocking rotational motion because of the speed of the tire rolling over it, it would have been free to continue to rotate until its energy was dissipated due to gravity. In other words, once the kinetic energy of the manhole cover exceeded its potential energy the manhole cover was free to exit the casting.

What would have been the limit of rotation and what would have been the height that the free end of the MH cover could have attained?

Procedures: Convert linear velocity downward of one end of the manhole cover, due to the rolling tire, to angular velocity of the manhole cover in motion:

$V_f^2 = V_o^2 + 2 \times g \times h$ Where h = Height difference between the seated manhole cover and casting seat from 1/8" to 3/4".

$\omega_f^2 \times r^2 = \omega_o^2 \times r^2 + 2 \times \alpha \times r \times h$

Where ω_f = Final angular velocity of the MH Cover = 0 (Vertical Direction)

ω_o= Initial angular velocity of rotation of the MH cover in rad/sec.

r = Radius of the MH cover in inches.

$V = \omega \times r$

$a = \alpha \times r$

The equation reduces to:

$\omega_f = 2 \times h / r \times t$ Where t is the time for the tire to roll over the MH cover.

$V := 30 \cdot mph$ $r := 13 \cdot in$ $t := \frac{2r}{V}$ $h := \left(\frac{1}{8}in, \frac{2}{8}\cdot in .. \frac{6}{8}\cdot in\right)$

$ang(h,r) := atan\left(\frac{h}{2 \cdot r}\right)$

$\omega(h,r,t) := \frac{2 \cdot h}{r \cdot t}$

h = (in)	ang(h,r) = (deg)	ω(h,r,t) = (rad/sec)
0.125	0.28	0.4
0.250	0.55	0.8
0.375	0.83	1.2
0.500	1.10	1.6
0.625	1.38	2.0
0.750	1.65	2.3

The angle and angular velocities are calculated. Calculate the linear velocity at the high portion of the cover. $v_f = \omega \times r / \cos(ang)$.

$v(h,r,t,ang) := \omega(h,r,t) \cdot r \div \cos(ang(h,r))$

v(h,r,t,ang) (in/sec)
5.1
10.2
15.2
20.3
25.4
30.5

Calculate the height the MH Cover would attain relative to the manhole thickness, (assuming the top of the manhole cover would have been even with the top of the casting), based on the tangential velocity generated by the angular velocity. If the manhole thickness is less than the height generated by the angular velocity the MH Cover could "jump" out of the casting.

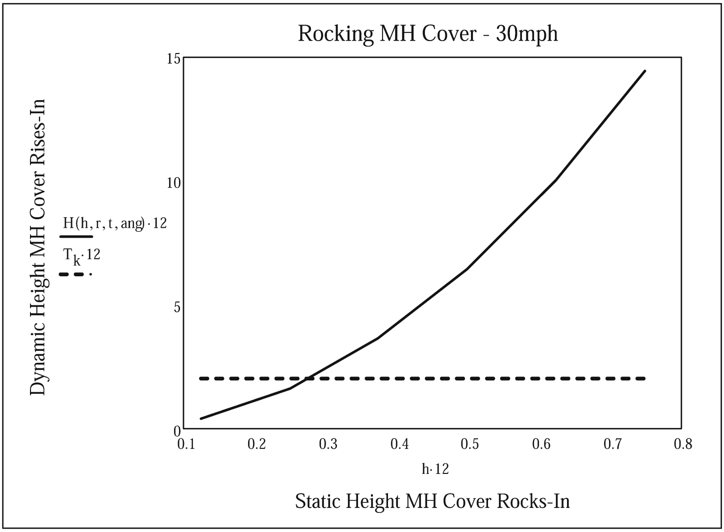
Thickness of MH Cover = T_k

$H(h,r,t,ang) := \frac{(v(h,r,t,ang))^2}{2 \cdot \frac{g}{12}}$

$T_k := 2 \cdot in$

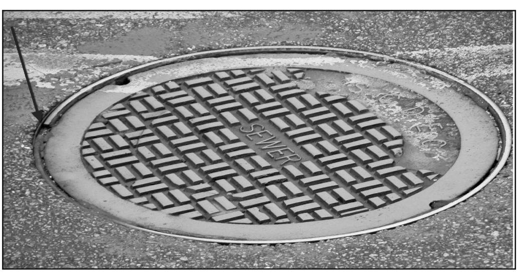
H(h,r,t,ang) (in)
0.40
1.60
3.61
6.41
10.02
14.43

The graph below was created for a rocking manhole cover where a tire rides over the manhole at 30 MPH. It shows that if the manhole cover had the ability to rock a minimum vertical distance of approximately 3/8", then it could clear the casting if the casting thickness and manhole cover thickness in this example were equal to two inches.



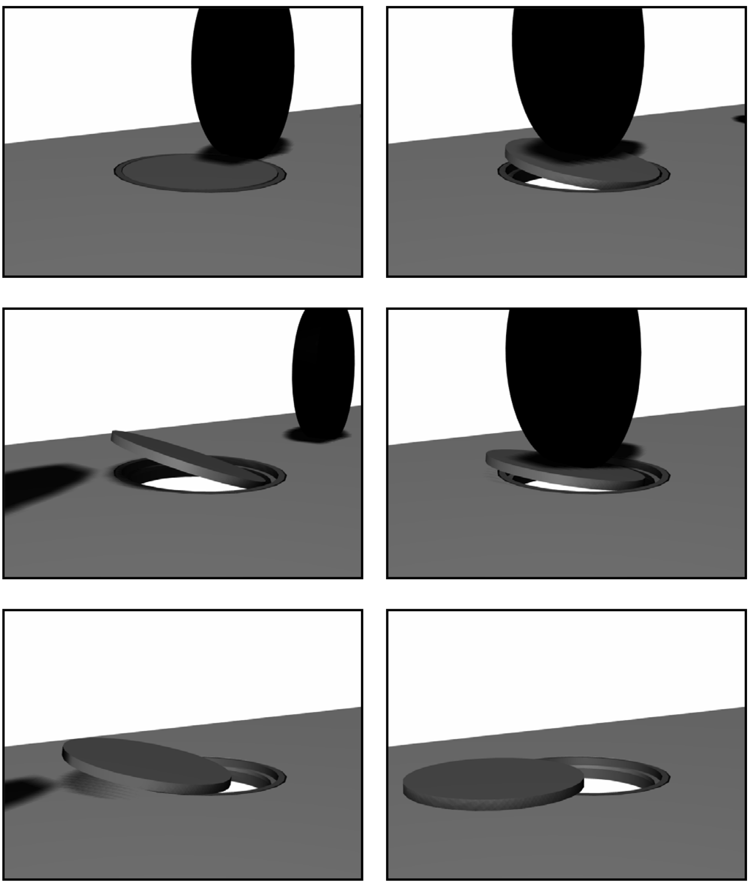
Material Aids

The sketch is an example of the adjustable riser ring. Notice that there is no method of preventing the edges where the turn buckle is located to move relative to each other in the vertical direction thereby creating a helix effect for the seat of the manhole cover if movement occurs.

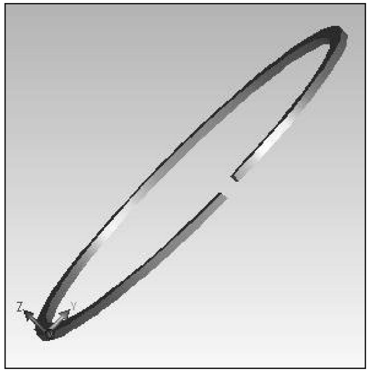


The arrow in the photograph is pointing to where the turn buckle would be located. Notice the height differential of the adjustment riser where it is split. Also notice the debris between the manhole cover and the sides of the adjustment ring which would prevent manhole cover motion. The debris would take some period of time to collect which would result in a stable manhole cover and prevent rocking.

The images below depict an 800 pound tire riding over a 26” diameter, 1” thick manhole cover that weights approximately 150 pounds. The manhole cover sits on a helix that has a pitch difference of 1/2” so that the manhole cover is not flush or even with the manhole casting. The helix emulates an adjustable manhole riser where the diameter of the adjustable riser varies depending on the diameter of the original manhole casting and the turn buckle or adjustment screw creates a pitch difference which causes the manhole cover not to have complete contact on the adjustment riser seat and therefore rocks within the casting. The manhole cover is allowed to rock and as a result when the tire rolls over it causes it to rotate and move out of the casting. The speed of the two tires is 30 mph at a distance of 110 inches which would approximate the wheel base of a vehicle. The orientation of the helix, and the location of the tire rolling over the manhole cover is random which may or may not cause the manhole to move in, as well as not move in the casting.



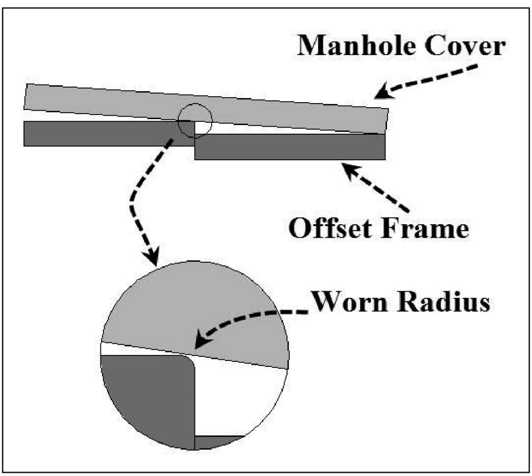
The adjacent helix represents the seat of the adjustable manhole riser on which the manhole cover sits. The diameter is approximately 26” with a difference in pitch of ¼” with a gap that represents the distance the turn buckle has expanded within the adjustable riser. The result is that the manhole cover does not sit completely on the seat and rocks relative to the pitch difference of the helix.



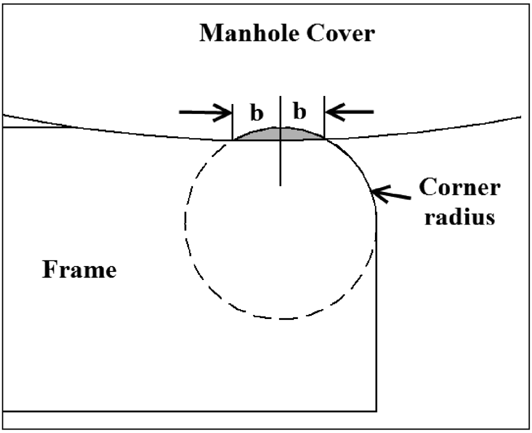
High Stress Concentration

The above calculations were based on the manhole cover being seated on a helix. If there was an obstruction between the manhole cover and casting seat, i.e.; a piece of metal or hard stone, then the manhole cover would be experiencing high stress concentrations at the point of contact between the obstruction and cover. Stress concentrations that would begin to propagate hairline cracks that would eventually cause failure of the cover when loaded repeatedly.

In the second instance where the probability existed that the manhole cover fractured, the strength of the manhole cover has been analyzed from the standpoint of the local contact stress originating at the corner where the manhole cover is lifted up at the end of the helix of the misaligned adjustment riser frame.



The local stress resulting from the manhole cover being supported on one small raised edge has been analyzed utilizing the Hertz Contact Stress analysis with the extension by Thomas and Hoersch who solved the three-dimensional stress field beneath the contact surface. The formulation of the analysis initially gives the local width of the deformed contact surface. The half-width "b" is calculated according to the diagram:



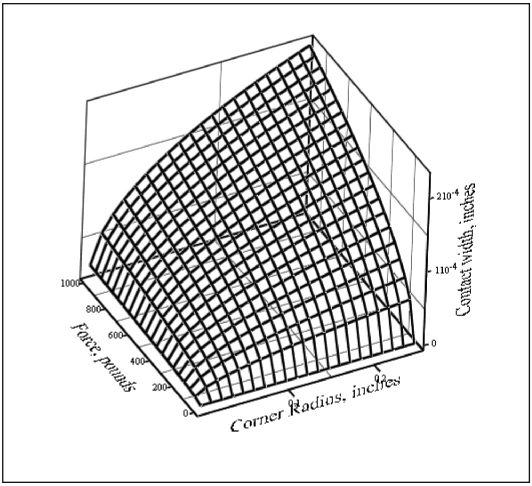
Where D is the corner radius and F is the load on the edge.

$$b_c(D_1, F_t) := \sqrt{\frac{2 \cdot F_t}{\pi \cdot l_c} \cdot \frac{\dfrac{1-\upsilon_1^{\,2}}{E_1} + \dfrac{1-\upsilon_2^{\,2}}{E_2}}{\dfrac{1}{D_1} + \dfrac{1}{D_2}}}$$

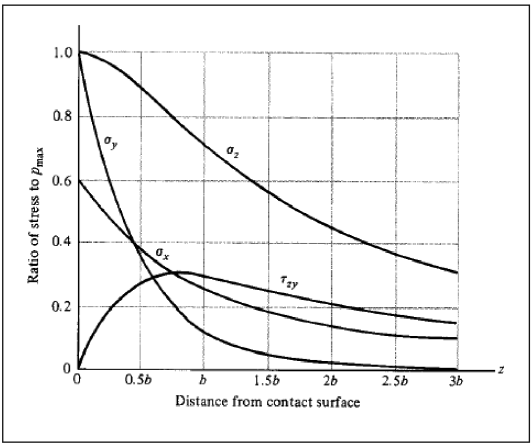
The specific solution for a 0.1 inch radius and a 500 pound load is:

$$b_c(.1 \cdot in, 500. \cdot lbf) = 1.389 \times 10^{-3}\ in$$

In graphical form, this is seen to depend on the corner radius and load as seen:



From this we can calculate the maximum pressure on the surface. With the maximum pressure the solution for the maximum shear stress can be determined from the graph from Thomas and Hoersch:



In this instance, the maximum shear stress is the indicator of the origin of failure, this being near the b-value below the surface and being 0.3 of the maximum surface pressure.

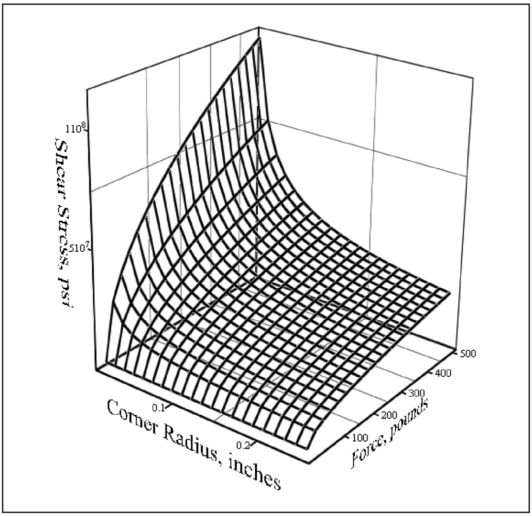
$$p_{max}(D_1, F_t) := \frac{2 \cdot F_t}{\pi \cdot b_c(D_1, F_t) \cdot l_c}$$

This is then calculated as before:

$$p_{max}(.1\cdot in, 500.\cdot lbf) = 2.291 \times 10^{5}\ psi$$

$$\tau_{max}(.1\cdot in, 500.\cdot lbf) = 6.874 \times 10^{4}\ psi$$

In Graphical form this is seen to be:



Conclusion

There was no explanation as to why the manhole cover could not be found. The defense claimed that it was stolen because it would not have rolled or slid very far from the manhole, although no one had ever looked inside the manhole to see if the manhole cover had failed. The continuous banging of the manhole from tire traffic would result in high stress concentrations and in turn would result in the propagation of stress cracks which would cause the manhole cover to fail. The verdict was in favor of the defendants in this case.