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DEFORMATION OF AN ICE COVER UNDER MOVING LOADS

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Many works have been devoted to the study of the deformation of an ice cover under various loads. In the basic studies the authors start by considering the action of static weights (1, 2, 3, 4, 5, 6, 7), while the effect of rapid changes of external forces is treated in only a small number of works. Thus, for example, Engineer Kashkin (8), using a mechanical recorder, showed that wave vibrations are produced in an ice cover after a blow from a weight. At the same time he came to the conclusion that the effect of these vibrations could be disregarded in calculating the strength of the ice. Professor Zubov (9) observed the periodic vibrations that occurred when a 70-ton load traveled along the ice. Noting the wave nature of a similar vibration, he suggested the possibility of the dangerous phenomenon of resonance.

Bregman and Proskuryakov (7) also cite data on the wave vibrations of an ice cover under moving loads, and think that there must be some critical speed above which the breakdown of the ice cover can result.

These brief observations have not found any great response among engineers and builders who are firmly convinced that static loads are all-important and that the vibrating processes in an ice cover are of little importance.

However, in the case of rapidly moving loads, experience on the Ladoga route has demonstrated that complications arise which are not considered

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in the theory based on study of the effect of static loads. The Administration of War Rehabilitation Works set us to studying this problem in connection with construction of the Ladoga Railroad. A detailed description of results obtained on Ladoga, on the Neva at the Shlissel'burg Bridge, and on Lake Suzdal' is published in a special collection UVVR-2 /"Authority of the War Rehabilitation Works"/, which deals with all the projects on the route. In this article we cite briefly only the main results of our work.

The deformation of the ice cover was measured with the aid of the "depressographs" (pogibografy) of the Reynov (10) system, which automatically noted the movement of the ice relative to the bottom of the lake. The wire, connecting the weight lying on the bottom with the recording apparatus set in the frame of the depressograph, went through the non-freezing ice hole (11), which was a pipe filled with lubricating oil. The lower end of the pipe extended below the lower surface of the ice. The series of depressographs was placed both perpendicular and parallel to the routes. This made it possible to record the shape of the depression curve of the ice and also the vibrations of the ice cover, and to measure their corresponding wave characteristics.

The experiment of studying the deformation of the ice cover under various loads (internal-combustion locomotives, automobiles, and other automobile transport) moving at a variety of speeds, showed the following:

1. Elastic deformation is observed with loads moving at speeds from 5 - 15 km/hr. The ice is depressed when the machines are crossing, and returns to normal after the crossing.

The shock spread through the ice with the speed of movement of the vehicles and vanished with practically the same speed.

Thus, the deformation consists of a curve of depression moving along the ice cover. In Figure 1, "a" is the record of the instruments placed perpendicular to the movement of the automobiles and 5 meters apart. Instrument No 1 was placed directly in the path.

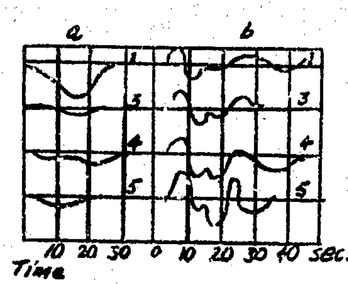

Figure 1

The magnitude of the depression in the case of slow movement, for example, is one-half to two-thirds as great as with purely static tests. Because of the short duration of the load the process of depression does not reach a state of elastic equilibrium due to the inertia of the displaced masses of water.

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2. When the loaded machines moved at speeds of more than 20 km/hr, there was a wave vibration which was recorded on apparatus as far as 100 meters away from the route.

One of the records of the depressographs, of an occasion when the loaded automobiles were moving at about 45 km/hr, is shown in Figure 1, b. Knowing the distance between the two instruments placed perpendicular to the direction of movement and by determining the time of retardation of the maxima of the respective curves, it was possible to determine the speed of propagation of the ice wave.

The period of vibration was determined directly from the graph as the distance between the two maxima or minima. By way of comparing the numerous curves at various speeds of movement and with different loads, both the velocity of the wave "v" and its wave length λ were measured. In our experiments with ice about 60 cm thick and a pond about 5 meters deep, = 200 meters and v = 35 km/hr, and this velocity did not depend on either the speed of the moving weight or on its magnitude. When the military situation did not permit installation of even two instruments, the wave characteristics were determined by a simplified method. Two holes were made in the ice about 30 - 50 meters apart. An observer with a stop-watch was stationed at each hole.

The vibrations of the ice cover caused a very noticeable change in the level of the water in the ice holes. Both stopwatches were started at the same time and the times of the minimum and maximum levels of the water were noted. This made it possible to determine the time it took for the wave to traverse the distance between the holes and also the period of vibration. Knowing the distance between the holes, it was possible to determine and "v". With very thick ice this method is applicable only when heavy loads are moved. In the case of speeds of the moving load which were less than the velocity of the wave, the latter outsped the automobile, and the apparatus began to register while the automobile was still approaching. However, in the case of speeds of the moving object greater than 35 km/hr, the recording of the wave vibration began after the automobile had passed.

On considering the cause of the waves in the ice, it can be said at once that they are not acoustic. The velocity of propagation of a sound wave in ice was observed in the experiment to be approximately a hundred times greater. At the same time the velocity of propagation of a shock in open water was much less. For example, when the length of the wave exceeds the depth of the water H many times, the velocity of the free wave is determined by Lagrange's equation: $v = \sqrt{gH}$.

In our case when H = 5 meters, v = 25 km/hr, that is, close to the velocity of 35 km/hr which we measured.

This makes it possible to conjecture that hydrodynamic waves cause the wave in the ice cover. The ice cover itself explains the deviation of the velocity of propagation of the wave from Lagrange's formula. The ice cover, deformed under the influence of the water wave which was produced, exerts a pressure from above on the surface of the water, which pressure is determined by the magnitude of the reaction of the deformed part of the ice cover.

In order to derive the approximate expression of the velocity of the single wave which travels under the ice cover, we will proceed from elementary considerations and use the law of the quantity of motion and

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the impact of forces. We shall call the thickness of the ice "d", the height of the wave "h", the weight of a unit of volume of the liquid γ, and the coefficient of elasticity of the ice sheet E.

The other designations remain the same.

The final expression for the velocity of the spreading of the wave under the ice sheet has the form:

$$v = \sqrt{gH\left(1 + \frac{\pi^4 E d^3}{24 \gamma l^4}\right)} \qquad (1)$$

Equation (1) is the result of the assumption of the propagation of a single progressive wave.

If equation (1) is applied to the conditions of the experiment we conducted, in which not single waves but a series of waves were created by the moving weight, that is, alternate rising and falling of the ice sheet were successively observed, then the results of calculating the velocity according to equation (1) will obviously be approximate. Equation (1) will be most closely descriptive of the velocity of propagation of the first positive wave of a series of waves under the ice cover recorded by the apparatus.

Actually, for the first positive wave, the condition of fastening the plate by the edges, which we assumed, will apply in the ice cover at the front end of the wave and will not apply at the rear end; that is, the bend in the line of deflection will coincide with the end of the positive wave and with the transition of it to a negative wave. Therefore, it would be more accurate in this case to consider the line of deflection of the plate with one edge fixed and the other swinging freely but not having freedom of horizontal movement. But since, in this case, the resultant equation becomes extremely complicated, and considering that for long waves with small amplitudes, this is the condition which determines the magnitude of the reaction of the ice cover "p", and that for the first positive wave no substantial corrections have to be introduced into the final results in calculation, we consider it possible to apply equation (1) as well to the obtained experimental data. It is not hard to see that when the thickness of the sheet of ice $d = 0$, equation (1) becomes Lagrange's formula.

Finally, as the wave length λ increases, the velocity of its propagation decreases, and at the limit when $\lambda = \infty$, it becomes equal to the velocity of propagation in open water, inasmuch as the ice cover, not being deformed, stops producing an additional impulse of force.

The theoretical problem of the possibility that the free wave will, after the impact of the water, overtake the moving load still remains to be explained. This problem is connected with the computation of the angle α, at which the waves are propagated. The theory of ship waves gives definite limits for these angles. In our experiments we did not measure the angle of opening. However, we observed many instances of waves overtaking loads on Lake Ladoga. We can only advance a hypothesis here. The fact is that in contrast with those cases considered in the theory of ship waves which operate from well streamlined contours, we were dealing with a contour having a very flat front, so that the water received not only

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impulses directed toward the motion of the load at a certain angle, but also impulses in the direction of the motion. However, upon receiving the impulse, the water wave is propagated further according to the law of the free wave with a velocity equal to

$$v = \sqrt{gH \left(1 + \frac{\pi^4 E d^3}{14 \gamma l^4} \right)}$$

If the speed of the load $c < v$, then the wave will travel away from it, and we will get a system of waves moving ahead of the load. However, when $c > v$, the load will outrun the wave. In this case, however, sustantial differences of the phenomena we described from the idealized case of the motion of a ship are included.

With slow movement, the greater the speed of the vehicle the smaller is the depression of ice in the path of the machine. However, with rapid motion, depending on the distance from the machine, the amplitude of the vibration increases and can attain magnitudes greater than the depressions with static loads. This condition is shown graphically in Figure 1. The same machine traveled at different speeds. If slow motion produced a large depression in the path, then in the case of rapid motion vibrations with amplitudes as great as, or greater than, the depression with slow speeds were observed 30 meters away from the path. Processes of interference which occur far away from the automobile are clearly evident in these same graphs. If the curve of depression near the path has a relatively simple shape approximating a sine curve, then the superimposition of one wave upon another, resulting in a considerable increase in amplitude, is clearly apparent at some distance from the path.

The interference of ice waves can be very important when several machines are in motion, and are passing each other in both directions. In this case, such complication of the amplitudes may occur that the ice breaks. Incidents of this kind were observed on the Ladoga route in 1942 and 1943. Such occurrences become especially dangerous when the machines are traveling at speeds corresponding to those of the propagation of the ice waves. In this case even one automobile going across alone can produce resonant vibrations in the ice causing it to break. All this explains the accidents, which have taken place on automobile routes, in which an automobile fell through while large numbers of other automobiles were passing, while the automobiles behind it went around the place where it fell through without experiencing any mishap.

Formula (1) makes it possible to calculate the coefficient of elasticity of the whole ice cover. We obtained the value E = 4000 kg/sq cm from our set of measurements.

The ice cover in the experiments consisted of a good crystalline ice with a thin layer of snowy ice frozen over it. The snowy sheet was completely pure and very solid (the automobiles did not fall through it) and was between 14 and 15 cm thick. The temperature of the air during the experiments was -6 degrees C, and the temperature of the ice was -6 degrees C.

The coefficient of elasticity thus obtained conformed very well, on the whole, with figures which we usually obtain in calculations. In the future, elaborate experiments to determine the coefficient of elasticity of ice fields of different composition must be conducted for various ponds and hydrometeorological conditions.

The rather small values of E compared to quantities which were calculated from the acoustic measurements of the samples of ice is explained

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primarily by the lack of uniformity of the actual ice cover.

We hall not mention here the results of our experiments in the study of 24-hour vibration of ice under the action of water and wind, or the study of the properties of an ice cover in juxtaposition to posts. They are discussed in detail in the above-mentioned compilation.

On the basis of the work done, it is possible to suggest a number of practical rules for the movement of vehicles along an ice route.

1. Avoid speeds close to the critical velocity of the propagation of the free wave. For our pond, which was 10 meters deep, these quantities fluctuated between 30 and 40 km.

2. As much as possible, maintain the initial speed, at 25 km/hr or 40 km/hr.

3. Do not overtake machines traveling ahead of you.

4. On ice which is not solid, do not cross in a body, but drive one vehicle at a time at a fast pace, which is in any case higher than the speed of propagation of the wave. The next machine can cross only after the lapse of time required for the vibration of the ice to die down. In our experiments, for example, this time was 3 minutes.

5. Even with ice which is sufficiently solid, try to maintain the above-mentioned time interval.

6. With rapid parallel movement of loads, the distance between them should not be set at less than 150 to 200 meters.

7. With slow movement of heavy loads, parallel movement may take place at a distance of 60 to 70 meters.

8. Particular caution must be exercised near the shores (at a distance of 50 to 70 meters), and meetings or bunching up of the moving vehicles must not be permitted here. Negative waves, which frequently produce complex amplitudes, are observed near the shores. This partially explains accidents involving vehicles on roads located close to the shore.

__Resume__

1. The deformation of ice under the action of moving loads has been studied.

2. It has been demonstrated that at speeds from 5 to 15 km/hr a movement of depression equal to the speed of movement of the load is observed.

3. With speeds above 20 km/hr, wave vibrations which were formed spread far to the sides of the route.

4. The formation of these waves was related to the generation the hydrodynamic waves produced by the movement of depression.

5. A formula has been derived for the velocity of propagation of the ice waves as function of the coefficient of elasticity, the thickness

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of the ice cover, and the depth of the pond.

6. The velocity of propagation of the ice waves ($v = 35$ km/hr), their wave length ($\lambda = 150$ meters), and the coefficient of elasticity of the ice cover ($E = 44{,}000$ kg/sq cm), have been determined.

7. The possibility of resonance, where speed of the moving loads equals the velocity of the propagation of the ice waves, has been demonstrated. In these instances, amplitudes large enough to cause the ice to break may develop.

8. Sample rules for the movement of automobiles along a route are given.

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