Thesis on the
Holyoke Dam,
by W. F. Huntington.
May. 1875.

The Holyoke Dam.

In the selection of a site for a dam, several things are to be considered.

I. The available fall. By this is meant the difference in height between the crest of the proposed dam, and the surface of the water in the river, at a point opposite the lowest waste-way. It is important that the fall should be as great as possible, particularly where large sums of money are to be expended in the erection of a dam.

II. The nature of the ground where it is proposed to erect the dam. It is desirable that the bed of the stream should be composed of rock or of some other material, capable of furnishing a firm foundation for the dam.

III. The locality must be favorable for the construction of canals and mills. There are many places where the available fall is as great as could be desired, but the configuration of the adjoining country is such, as to render the building of canals and mills a task of great labor and expense. A rocky gorge would not furnish a good site for a dam, because the water power that would be made available, could be utilized only at great expense. It is best if possible to select a place where the banks of the stream below the dam rise with a gradual slope. Then canals can be built parallel to each other and at different grades, so that the water that has been used in driving the machinery of the mills situated along the highest canal, can be discharged into the canal immediately below and used again.

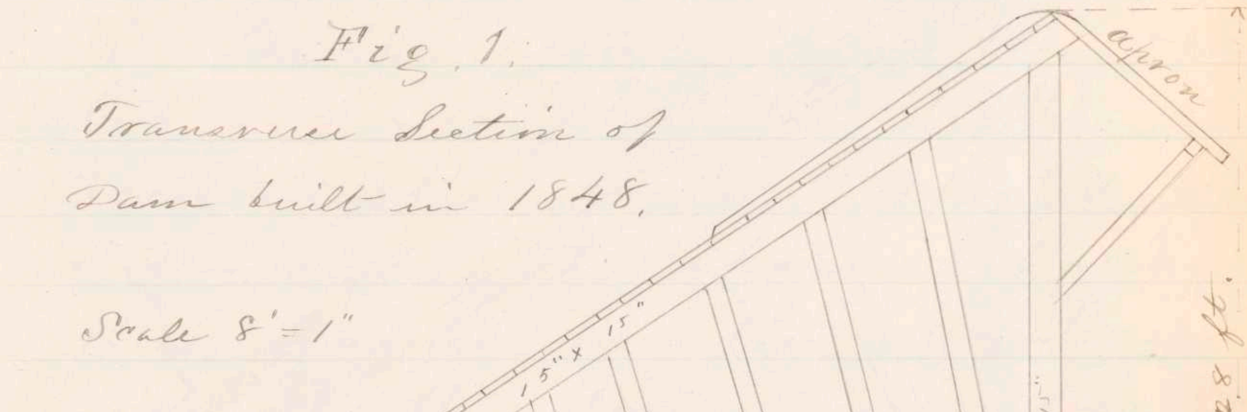
The site chosen for the Holyoke Dam seems to possess all the advantages that could be desired. There is an available fall of upwards of 60 feet. The bed of the river at the place where the dam has been built, is composed of red sandstone rock, and the banks on either side are of the same material. This red sandstone, or Connecticut River sandstone as it is usually called, furnishes an excellent foundation for the dam, and the masonry of the abutments and head gates. The lay of the land below the dam is peculiarly adapted for the construction of the necessary distributing canals, and as the surface of the ground is composed of fine sand that can be easily excavated, they can be built at comparatively small expense.

As early as 1845 the attention of certain capitalists had been turned towards the immense though as yet unemployed water-power, afforded by the Connecticut River at Hadley Falls. It was seen that if a dam of sufficient height and strength could be thrown across the river at the Falls, unusual opportunities would be afforded for the progress of manufactures. In the fall of 1846 Mr G. C. Ewing, of the firm of Fairbanks & Co of New York, began negotiating for the purchase of land in the vicinity of the Falls. Before the close of the summer of 1847, he had succeeded in obtaining possession of about eleven hundred acres. A joint stock company now formed with a capital of $2,000,000. Mr John Chase of Chicopee and Mr Philander Anderson, a graduate of West Point, were appointed engineers of the company. This new company proceeded to erect a dam across the river, which was completed Nov 19. 1848.

I will now give a description of this dam. The dam was about 1000 feet long, and varied in height from 28 to 30 feet. Mr Jonas Kendall of South Framingham, who supplied the iron used in its construction and who was frequenly present while it was being built, has kindly furnished me with a sketch of the dam. Althoug this sketch may not be perfectly correct in all its details, yet it serves to give a good idea of the form of the dam. Below is a copy of the drawing sent me by Mr Kendall.

Fig. 1.
Transverse Section of Dam built in 1848.

Scale 8' = 1"



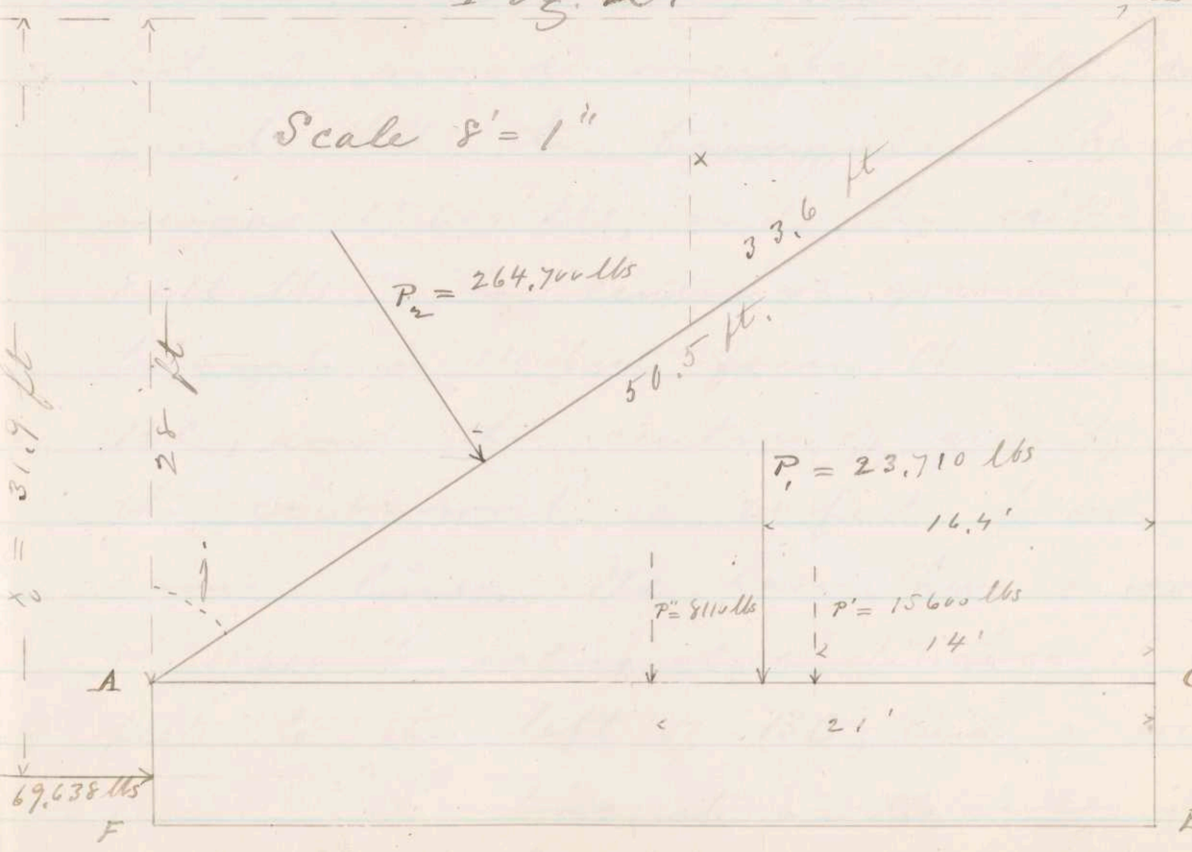
The dam consisted of a series of triangular frames resting upon a foundation of crib-work. Each frame was 28 feet high, and measured 42 feet along the base. The frames were placed 6 feet from centre to centre. Where the bed of the river was not more than 28 feet below the crest of the dam, the frames rested upon the rock, but in places where this depth was exceeded, they were supported by crib-work. The space between these frames on the up stream side of the dam, was closed by a floor of six inch plank. In order to protect the rock in front of the dam from being worn away by the action of the falling water, an apron of plank was built at the crest of the dam, as shown in the sketch. The timbers of the dam were all bolted together with iron bolts, and the base of the structure was fastened to the rock in the same way.

The dam was built in sections two or three hundred feet in length. On the up stream or sloping side, gates were provided, so that during the construction of the last section, the water in the river was allowed to flow through the gates of the completed sections. As soon as the whole was finished, the gates were closed, and the water behind the dam immediately began to rise.

But the dam was not capable of resisting the enormous pressure brought to bear upon it, and when the water had arisen within a few feet of the crest, it gave way. The dam broke in the centre, and about two thirds of the structure was carried down stream. Soon after the gates were shut down leaks were discovered, but all attempts to stop these leaks failed, and they kept increasing until the dam finally gave way. One reason given for the failure of the dam is, that the foundations were undermined by the water which escaped from these leaks. Mr Mills, the engineer of the Lawrence Water Power Company, says that the pressure of the water caused the dam to slide along its foundations, and the computations which will be given later, seem to substantiate this statement. In justice to the engineers employed by the Hadley Falls Company, it may be said that the dam was built contrary to their advice. They recommended the building of a stronger as well as more costly structure, but a spirit of false economy prevailed, and the cheaper plan was adopted.

Let us now find the forces which act upon the dam, and determine whether it was theoretically capable of resisting the pressures brought to bear upon it. In order to do this, it is necessary first to construct a diagram representing an outline of a transverse section of the dam. The following is such a diagram.

Fig. 2.



We will make our calculations on the supposition that there is no water surrounding the foundation of the dam. As the triangular frames are placed 6 feet apart, the most convenient way of proceeding, is to calculate the forces acting upon a section of the dam 6 feet in width. Let us first find the weight of the timber in such a section. Assuming that a cubic foot of wood weighs 30 lbs, we find that the triangular frame weighs 15600 lbs, and the crib-work 8110 lbs. The centre of gravity of the triangle is 14 feet from the line BC, and the centre of gravity of the crib-work is 21 feet from the same line. We have then a force of 15600 lbs acting at a distance of 14 feet to the left of BC, and a force of 8110 lbs acting at a distance of 21 feet to the left of B.C. By the principal of moments, we find that their resultant is a force of 23710 lbs. acting at a perpendicular distance of 16.4 feet to the left of BC. Let us now find the total pressure of the water upon the sloping face of the dam. If the up stream side were vertical instead of sloping, the pressure on any small part, would be simply proportional to its distance below the surface of the water. Let w be the weight of a unit of volume of water, Call the width of the section z, and the vertical distances measured downward x. Then the pressure on a unit of surface is $wx\,dz\,dx$, and the pressure on a band of length z and depth dx is $wx.z\,dx$. But in the present case the sloping side makes an angle with the vertical which we will call j, so that the area of this band is increased by the sec. of j, and

the pressure on the band becomes $wxz\,dx \sec j$. The total pressure on the surface is $P = \int_0^x wxz\,dx \sec j =$
$= z \frac{wx^2}{2} \sec j$. Now $w = 62.4$ lbs, $z = 6'$, $x = 28'$, $\sec j = \frac{50.5}{28} = \frac{101}{56}$. Substituting the above values in the formula we have:

$$P = \frac{6 \times 28^2}{2} \times \frac{101}{56} = 264700 \text{ lbs.}$$

This force acts in a direction perpendicular to the sloping plane, and at a distance from B measured along the slope towards A, of 33.6 ft. It remains for us to find the total pressure acting on the vertical plane at the toe of the dam. Our formula is $P = \int_{x_2}^{x_1} wxz\,dx$. Now $w = 62.4$, $z = 6'$, $x_1 = 34$, $x_2 = 28$, Substituting these values we have:

$$P = 6 \times 62.4 \int_{28}^{34} x\,dx = 6 \times 62.4 \left(\frac{34^2}{2} - \frac{28^2}{2} \right) = 69638 \text{ lbs.}$$

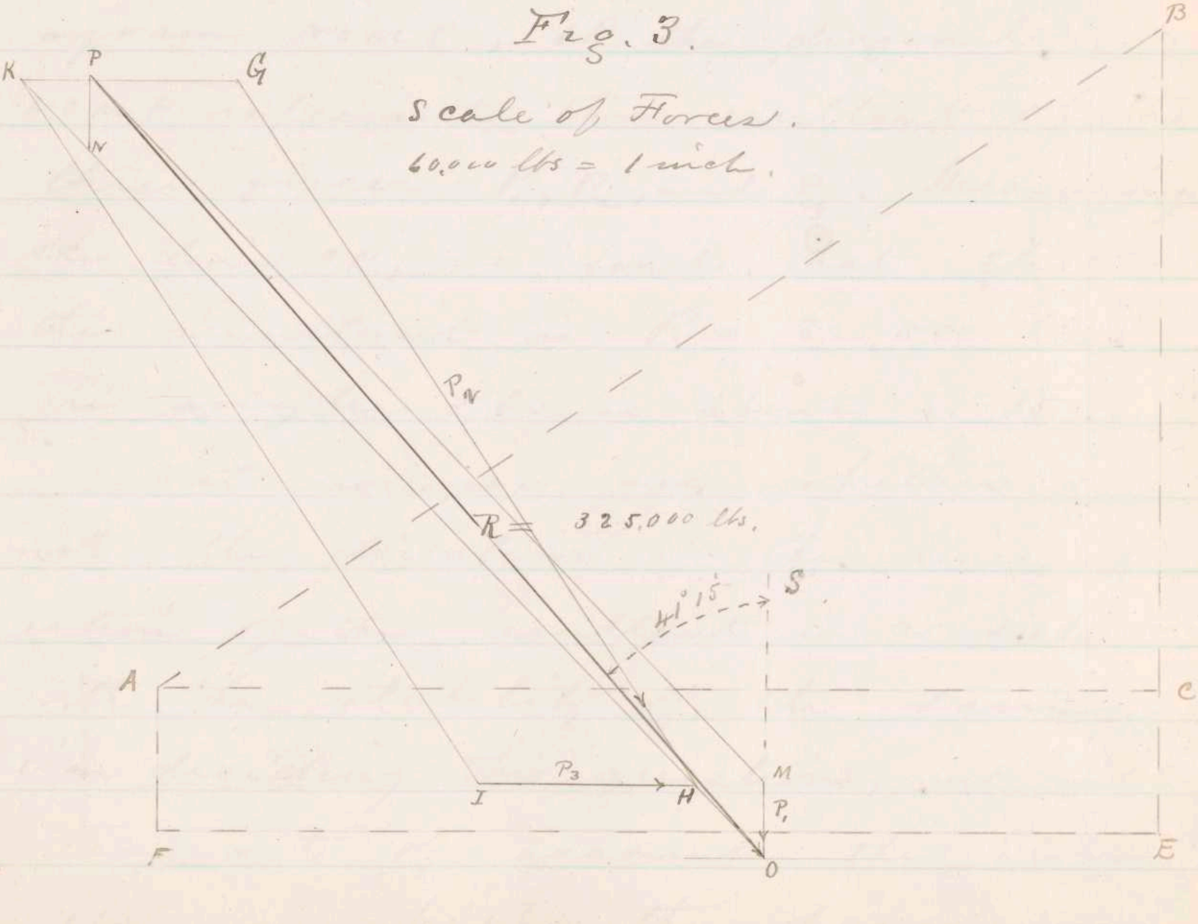
This last force acts at a distance below the surface of the water given by the formula: $x_0 = \frac{2}{3} \frac{x_1^3 - x_2^3}{x_1^2 - x_2^2}$. Now as before $x_1 = 34$, $x_2 = 28$, and hence

$$x_0 = \frac{2}{3}\left(\frac{34^3 - 28^3}{34^2 - 28^2}\right) = \frac{2}{3}\left(\frac{39304 - 21952}{1156 - 784}\right) = 31.9 \text{ feet.}$$

It will be sufficiently accurate for our purpose, if we find the magnitude direction and point of application of the resultant of these three forces by the graphical method. Let us first draw the lines AB, AC, EF, in the same relative position as they are drawn in Fig. 2, page 10.

Fig. 3.

Scale of Forces.
60,000 lbs = 1 inch.



We will next draw the lines of action of the three forces P_1, P_2, and P_3, in their proper positions as shown in the diagram, and we will represent the magnitude of each force on a scale of 60000 lbs = 1 inch. Constructing the parallelogram of forces GHIK, we find that the resultant of P_2 and P_3, is represented by HK. Take NO = HK, and draw the parallelogram NOMP, OP the diagonal of NOMP represents the resultant of the three forces P_1, P_2, and P_3. Measuring the line OP, we find that that the resultant is R = 325,000 lbs. The angle POS is about 41° 15'.

Let us now see whether or not the direction of the line of action of the resultant is consistant with the stability of the dam. In deciding this question, we will leave out of account the iron bolts by which the dam was fastened to the rock, for although they may have increased its strength to some extent, it should have been strong enough in itself to resist the pressure of the water. The stability of a retaining wall depends on two conditions viz: Stability of position, and stability of friction. It is evident that there is no tendancy in the dam to give way by overturning, so that the first of these conditions is fulfilled. Stability of friction will be secured, if the resultant pressure makes with the vertical an angle not greater than than the angle of repose of wood on stone. In the table on page 211 of Prof. Rankine's Applied Mechanics, this angle is given as 22°. Now in the case in hand, the angle that the resultant makes with the vertical is 41° 15'. As this angle is nearly twice as large as it should be, it is evident the condition of stability of friction is not fulfilled.

The conclusion which may be drawn from what has been said, is that the dam was improperly constructed. The angle of the inclined side should not have exceeded 22°, and the slope should have been continued down to the rock. The structure should have been still further strengthened by a ballasting of stone.

Although the failure of the first dam built across the Connecticut River at Hadley Falls, was a source of great disappointment to its owners, yet they had already invested so much money in the enterprise, that they could not afford to give it up. A new dam was commenced in the Spring of 1849, and completed

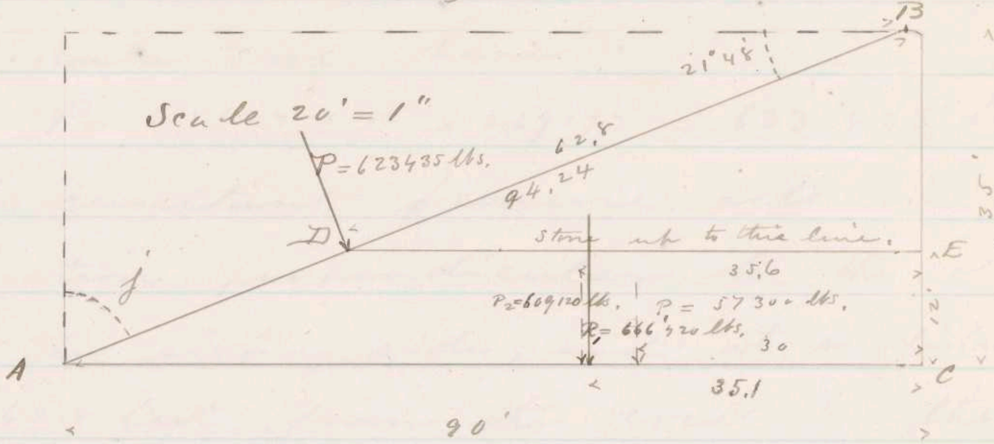
Oct 22. 1849. This structure was designed and built by Messrs Chase and Anderson, who have been previously mentioned as having been engaged in the erection of the first dam. A section of the new dam is shown on Plate 1. It consists of a series of timber frames placed 6 feet apart. These frames are made up of alternate courses of rafters and blocks. The rafters slope at an angle of 21°48'. The lower end of each rafter is bolted to the rock. The short blocks are intended to stiffen or prevent the bending of the rafters. At the splicing of the rafters longer pieces are put in and fastened to the rafters with two inch treenails. The frames are tied together by square sticks of timber, running across the river. The rafters, blocks and ties are all 12"x12" timber. The construction of the dam was commenced by building two coffer dams; one on each side of the river and extending 200 feet from the bank. The water was then pumped out, and the rock excavated to a depth of 6 feet. Three pieces 15"x15" were then laid lengthwise across the river. The rock was first cut so that when the sticks were put in place, their upper surface was inclined at angle of 21° with the horizon. These three pieces are shown at the bottom of the front of the dam. Above these pieces the rafters, blocks, and ties, were laid in courses as has been stated on the previous page. The up-stream side of the dam was covered with a floor of six inch plank, with the exception of a space 16 feet wide left temporarily open. The toe of the dam was secured by placing a second covering of plank at right angles to the first, and over this a layer of beton as shown in the plan. The crest for 4 feet on the up stream side was covered with 3/8" boiler iron to protect the top from the blows of drift wood and ice. A double thickness of plank was also given the crest for the same purpose. The interior of the dam was then filled with stone to a depth of 12 feet. The dotted line across the section of the dam shows the height to which the ballasting was carried up. The space behind the dam was then filled in with sand as shown in Plate I.

In the above manner two sections 400 feet in length were completed, 200 feet on each side of the river. These sections were then each extended 200 feet farther, leaving a space of 219 feet wide through which all the water in the river was compelled to flow. A coffer dam was then built 4 feet higher than those that had been used in the building of the other sections. The water being now confined within the space behind the dam rose to a depth of 12 feet. It will now be seen that the open space left in the up stream side of the dam, was left for the purpose of providing an outlet for the surplus water which began to accumulate, as soon as the open space just spoken of was closed. A part of the opening at each end of the dam was closed, leaving 828 feet to be closed by gates. A side view of one of these gates is shown

in the section of the dam on Plate I. Each gate was 18 feet long and 16 feet wide, and was attached to the plank-ing by hinges. While the dam was being built, the gate was supported in a horizontal position by means of wooden props as shown in the side view of the gate, this prop was arranged so that it could be thrown out of position when the gate was to be closed. The dam was completed Oct 22, 1849. The gates were all closed on the morn-ing of that day, and in about nine hours afterwards the dam filled and the water went over the crest.

Let us now take a section of the dam, and calculate the forces acting at that section. As the frames are placed 6 feet apart, we will take a section 6 feet in width. The calculations will be best understood by the aid of a diagram.

Fig 4



The total weight of the timber in the section is P_1 = 57 300 lbs. The total weight of the stone is P_2 = 609120 lbs. In the diagram we have P_1 = 57 300 lbs acting at a distance of 30 feet to the left of BC, and P_2 = 609 120 lbs acting 35.6 feet to the left of BC. The resultant of these two forces is R_1 = 666 420 lbs, acting at a perpendicular distance of 35.1 feet to the left of BC. Let us next find the pressure of the water upon the up stream side of the section. The formula is the same as that used on page 13, $P = 3\frac{wx^2}{2}\sec j$.

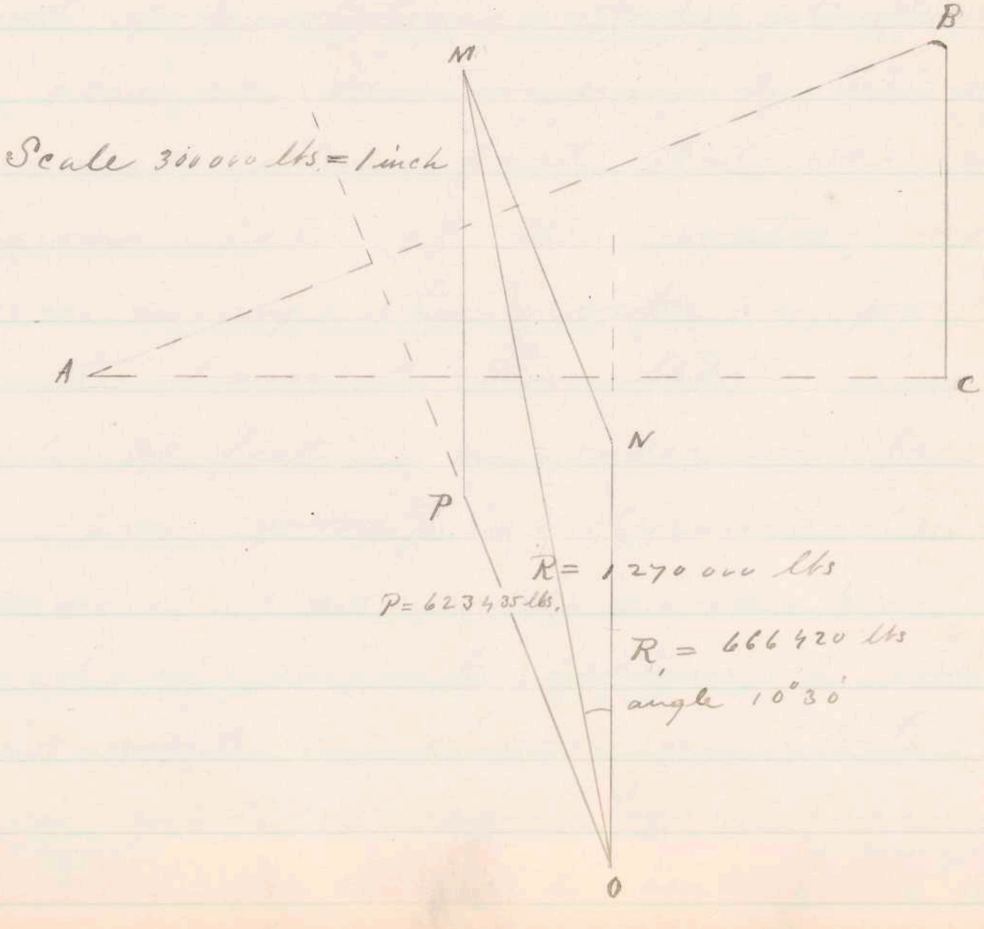
In the present case $w = 62.4$ lbs, $x = 35$;
$z = 6'$, $j = 90° - (21°48') = 68°12'$ sec $j = 2.69273$.
Substituting the above values, in our formula we have:

$$P = \frac{6 \times 62.4 \times 35^2}{2} \times 2.69273 = 623\,435 \text{ lbs.}$$

This resultant pressure acts in a direction perpendicular to the plane of the sloping side, and at a distance of 62.8 feet from the crest of the dam measured along the slope.
Let us now find the resultant of the two forces R, and P, the first being a force due to the weight of the dam, and the second a force due to the pressure of the water behind the dam. This is done most easily by a graphical construction as shown on the next page.
By drawing a parallelogram of forces, the resultant is found to be a force R = 1270 000 lbs acting along the line MO, and at a perpendicular distance to the left of BC of 44.6 ft. The angle

MON. is 10° 30'. It is evident from the diagram, that both conditions of stability mentioned on page 16 are fulfilled. The angle of repose of dry masonry is given as 35°. So that the angle MON is only $\frac{2}{7}$ of the angle of repose.

Fig 5.



I will now say a few words about the crib-work of logs and stone, which was commenced in 1868, and completed in 1870. In the spring flood of 1868, the front timbers of the dam were slightly loosened by the concussion of a heavy bridge, which came down on the flood from some point a hundred miles above. An examination of the front foundations, while it disclosed no very serious injury to the dam, revealed the fact that the continuous fall of the water had worn away the rock in front of the dam to the depth of from 26 to 30 feet. In order to prevent the dam from being undermined, an apron of crib-work was built in front of it. A section of this crib-work is shown on Plate I. It is made of large logs placed 7 feet from centre to centre. The logs are notched and bolted together with iron bolts. All the open space between the logs is filled in with stone. The front of the crib-work is covered with 12"x12" sticks pinned to the timbers underneath; and upon these pieces are spiked plank four inches thick. It should be stated that the open space that was left in the upper part of the dam when it was built, was filled in with stone during the construction of the crib-work.

The abutments of the dam, the head gates for regulating the flow of water in the canals, the over-falls, the sluices, and the locks intended for the passage of boats up and down the river, have all been built in the most thorough manner. The head gates, the abutment, and the lock, on the west side of the river, are shown in Plate II. Fig. 1 is a plan of the head gates, abutment, and lock just mentioned, Fig. 2 is an elevation of the same. Fig 3 is an end view. Fig. 4 is a section of the masonry of the head gates taken at the line A B Fig. 1. Fig. 5 is a section taken at the line C D Fig. 1. It is intended in this section to give a side view of a pier from the foundation to the floor of the gate house. The machinery for raising the next gate is also shown. This machinery consists of a system of gearing by which a great gain in power is made, but at the expense of a corresponding decrease in speed. The upright piece of timber shown in the elevation, is attached to the gate below. A firm bearing is given this timber against the gearing of the machinery, by a small wheel on the right hand side of the timber. This wheel is not represented in the drawing. The machinery is driven by a small water wheel, which is located in the open space between the abutment and the masonry of the head gates. The wall surrounding the wheel is shown approximately, by the dotted line in Fig. 1. Figs 6 and 7, are a top and front view of a gate. Fig. 8 is a side view of the same. Fig. 9 is a rear view of one of the timbers attached to the gate, showing the iron plate upon which the wheel spoken of above rools.

The volume of water flowing in the river at Holyoke at ordinary times, is estimated to be 5200 cubic feet per second. The available fall is 60 feet. The power made available, expressed in foot pounds per minutes is:

P = 5200 × 60 × 60 × 62.4 = 116,812,800 ft lbs. per minute. Dividing by 33000, we find that this is equivalent to 35.400 horse powers.

This immense power is distributed by means of three canals, each at a different level. The surface of the water in the first level canal, is at grade 100.00 or at the same height as the crest of the dam. The fall from the first level to the second is 20 feet, and from the second to the third 12 feet. The greatest fall from the third level to the river is about 28 feet.

The map of Holyoke which accompanies this thesis, shows very clearly the position of the dam, the head gates, and the canals,

Remarks.

I should have said on page 17, that my calculations seemed to show that the dam gave way by sliding along its foundations. The structure may have slid along the rock, or the timbers of the lower part of the dam may have slid upon each other. Mr Mills of Lawrence, thinks that the triangular frames slid upon the crib-work underneath.

In the calculations the weight of a cubic foot of wood has been taken as 30 lbs. This value may be too small, but if it is, then the calculations are on the safe side.

The weight of stone has been taken as 144 lbs. per cubic foot.

The timber used in building both dams, was mostly hemlock and chestnut: the timber in the apron is nearly all chestnut.

The stone used in filling in the dam and apron, was taken from the bed of the river.

The cost of the first dam was $ 100.000. The dam built in 1849 cost $150,000. The apron which has been built in front of the dam cost $250,000.

Fig. 1, Plate I, is intended to show the manner in which the timbers are arranged longitudinally.