Architectural Conservation and Historic Preservation
Prof. Sanghamitra Basu
Department of Architecture and Regional Planning
Indian Institute of Technology, Kharagpur

Lecture - 27
Investigation and Conservation of Historic Structures Case Study 1

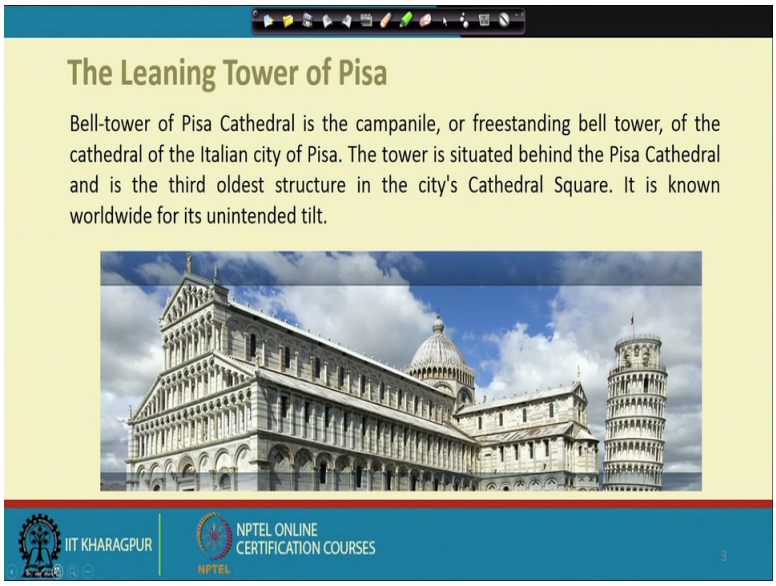
In the last lecture, we discuss about the different types of documentation of the historic structures and on the various aspects and today, we will talk about some of the case study to show and we also talked about the importance of the investigation and diagnosis. So, today, we will talk about a case study where we will see the; what is the rule or importance of the diagnosis and investigation and how that if it is not done properly how it can lead to a very disastrous effect.

(Refer Slide Time: 00:51)

If you remember that we have talked about problem identification diagnosis and intervention option and that how that leads to the conservation strategy.

So, the case study what I am just trying to discuss with discussed today is a very famous case this is the leaning tower of Pisa.

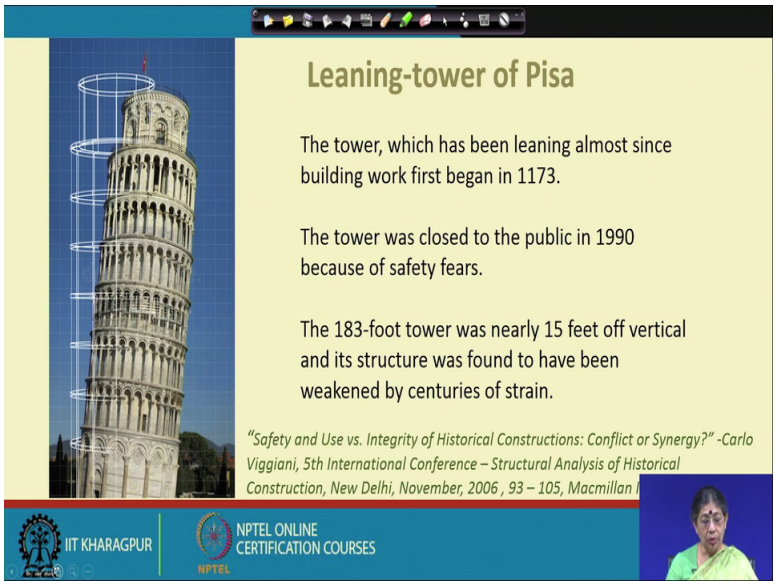
(Refer Slide Time: 01:09)



Now, the leaning tower of Pisa is a historical structure it is actually the bell tower of Pisa cathedral is the campanile or freestanding bell tower which is the attached to the related to the cathedral in the Italian city of Pisa the tower is situated behind the cathedral and is the third oldest structure in the city cathedral square it is known world wise because of his unintended tilt.

So, we will talk about that why this tilt happen, how this tilt happened and what is the impact of that and how it has been how and what are the remedial measures which has been taken and how the decision was taken about it, it is a long story.

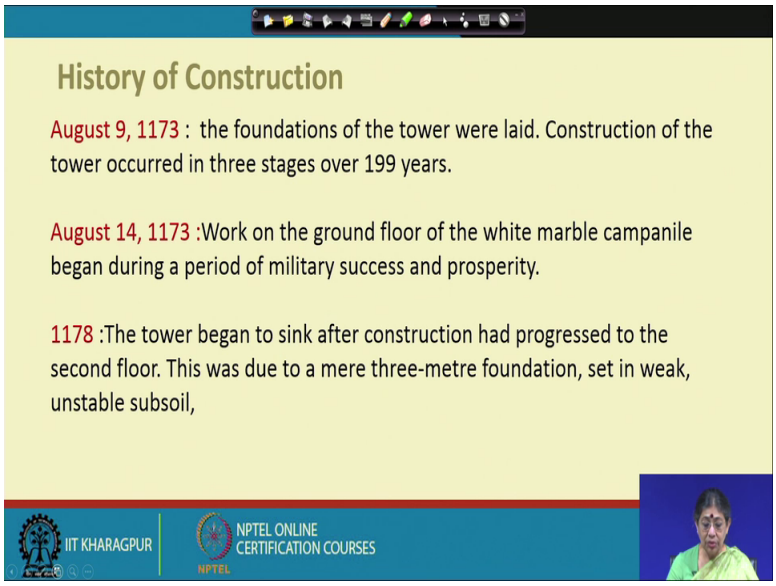
(Refer Slide Time: 01:54)



Now, as we can see here that I mean the tilt is quite a lot the tower which has been leaning almost since the billing work first began in 7; 1173 and the tower was closed to the public in 1990 because of the safety fears and the 183 foot tower was nearly 15 feet off vertical and its structure was found to have weakened by centuries of strain.

So, what are you following is this a article which has been published and you can also searching to the Google, you will get it. So, there has been a very comprehensive study and discussion about the history of the tilt and what has been done and how the remedial measures have been taken. So, I am referring this particular article for my presentation today.

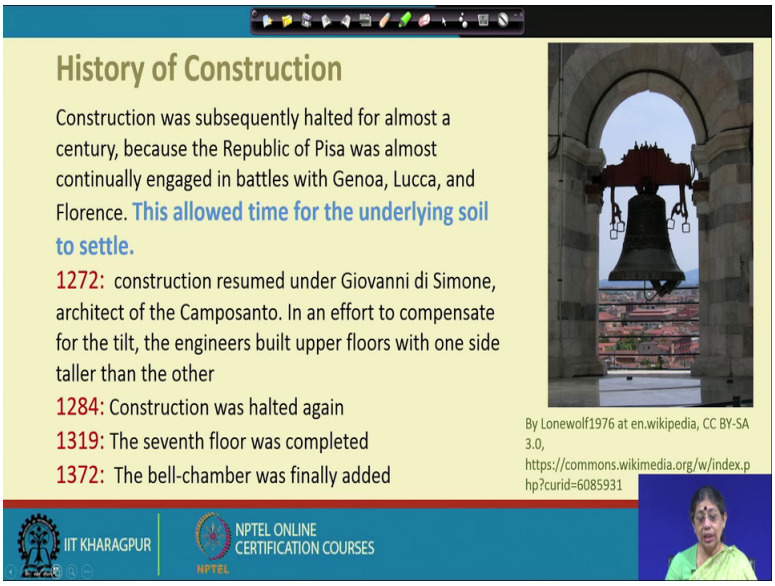
(Refer Slide Time: 02:55)



Now, let us see the history of construction how it happened the construction is started first in 1173, in the August, the foundation of this tower was late and construction of that occurred and basically, it occurred in three stages over almost a period of 200 years. So, 1173 the work on the ground floor started and white marble campanile began during a period of the military that was the time when Italy was different states of Italy and this was prosperous period of that and during that time if the construction started.

Now, immediately after it started construction, by 1178 the tower begin to sink after construction has progressed to the second floor, not even to the present on it, even after second floor and the reason was that the foundation this such a long tower, it was intended, but the foundation was only three metre foundation and also the subsoil; the subsoil was very weak and unstable subsoil. So, you can see that it was a design that is flawed right from the beginning.

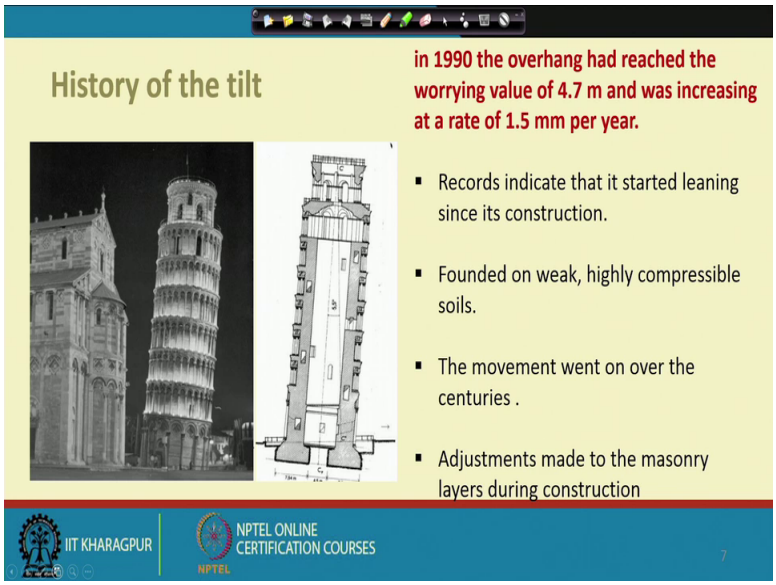
(Refer Slide Time: 04:13)



The construction when this was noticed that it started tilting, but also you must understand that any construction any superstructure when is constructed, there may be some adjustment of the ground, they will try to sort of a balance and other thing that always happens, but when it is continuous and if there is an unequal settlement and if it is continued for a long time; that is very dangerous. So, the construction because of this tilting, the construction was actually halted for almost a century and there were other reason also because it was also a lot of battles were happening between the; amongst the various states of these things and it is also is a boon in disguise because it also allowed the time for underlying soil to settle down.

In 272, the construction was again resumed and there was an particular architect Camposanto and in an effort to compensate for the tilt because the realised that the tilt test, there the engineers built the upper floors with one side taller than the other. So, there was a realisation that in the superstructure some sort of adjustment will be required, but in 284, the construction was halted again and by 1390. So, it was sometimes due to the construction, sometimes due to the battle which is going on. So, there were various reason and by 1319, the seventh floor was also completed and by 1372, the bell chamber; what is the major purpose of this tower is the bell tower is basically bell tower. So, the bell chamber was finally, added.

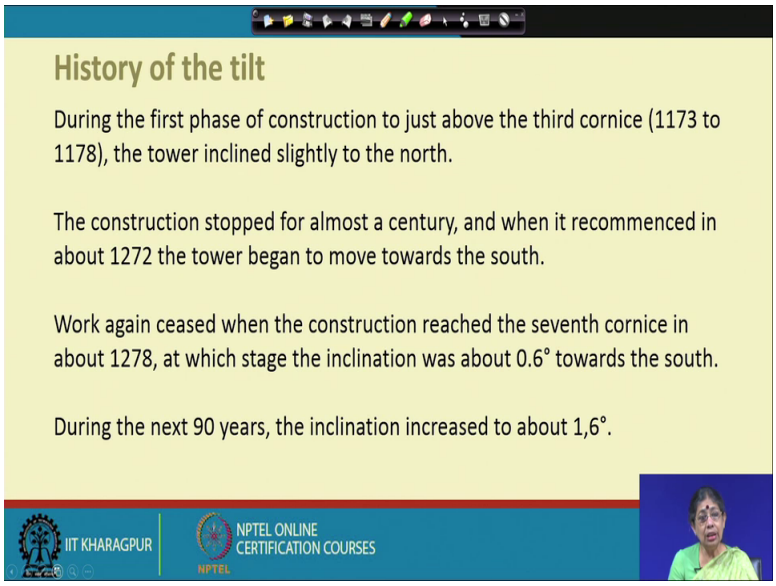
(Refer Slide Time: 06:01)



But 1909, the overhang had reached the worrying value of four point seven metre and was increasing at a rate of 1.5 metre per year. So, what is very worrying situation was that not only it has tilted a lot, but tilt was continuing. So, there were records the records indicate that it started leaning since its construction, but the history says that if you can summarise the points here, it was founded on a week at highly compressible soil and the movement went on for centuries and adjustment was made during the construction in the masonry layers of construction.

So, these are the some of the points, we have to remember that the soil condition was bad, there was a faulty designed and it started right from the beginning and there was a gap in the construction time and the movement was continuing for centuries, but also one must remember that the movement did not happen at a uniform rate.

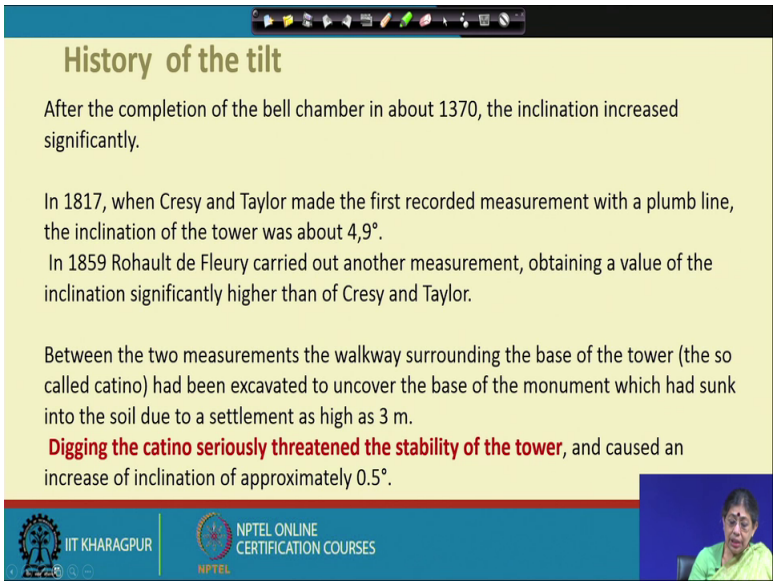
(Refer Slide Time: 07:11)



So, let us say the history of the tilt during the first phase of the construction to just above the third cornice the tower inclined slightly to the north. So, what will see that the even the tilt was not in one direction, the tilt was also changing in this direction, then the; say it was an initial adjustment and it almost stopped for a century and in 1272 when it was again resumed it try to began to south. So, we see that the there was a tilting effect and the tilt in first it was north and then it was towards the south.

So, the direction changed the work again ceased when the construction reached the seventh cornice in about 1278 at which stage the inclination about 0.6 degree towards the south. So, it was at a rotational inclination and during the next 90 years, the inclination increase about one. So, what we have to see that the inclination change; the direction another is the inclination was increasing over the years almost along years.

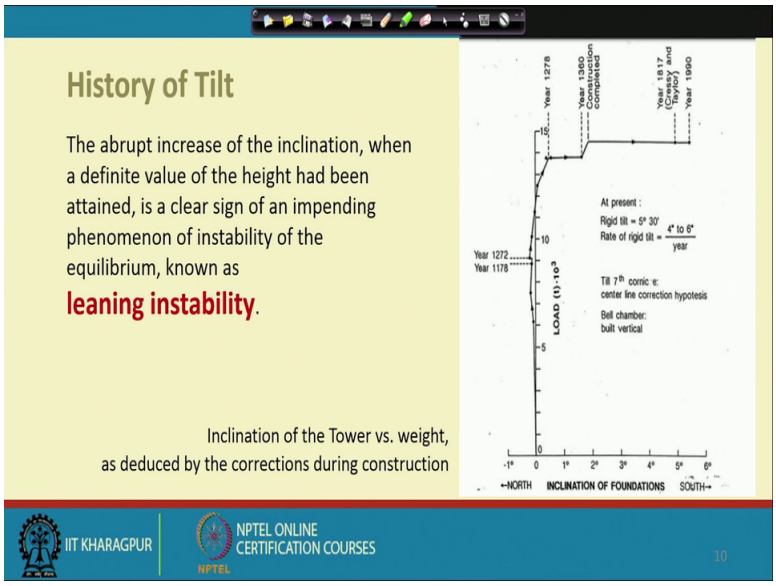
(Refer Slide Time: 08:19)



After the completion of the bell tower in 1370, the inclination increase signified significantly in 1870, the there was they started recording the first measurement with a plumb line to see what was the inclination and there were record that from that time onwards that. So, and then subsequently 2-3 records were there. So, we have a record that what was the inclination and which year. So, some sort of a rate and understanding and it can be the related with the construction history between the two measurements the walkway surrounding the base of the tower which is called Catino, there is a base had been excavated to uncover the base of the monument which had sunk into the soil.

So, one side of that base at actually really sunk into the soil and the settlement was as high as 3 metre, quite a lot and it was also found that when that Catino was digging stag, it is seriously threatened the stability of the tower and caused an increase of inclination to approximately 0.5 degree. So, as you can see that some sort of intervention some adjustment was going on there was a realization, it stopped and halted, but when something was being done. So, some intervention actually change the not only induce the rate, but it also the degree of the inclination of the direction of the inclination also change.

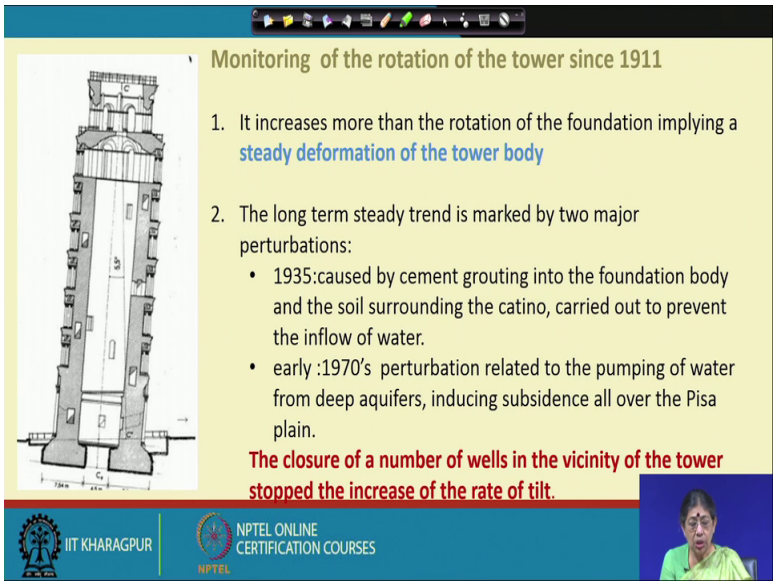
(Refer Slide Time: 09:48)



So, you can see that this is an interesting record what we can see which shows the inclination of the foundation. So, as we can see that here, you can see that here, it actually, it actually first the direction was done and then we have a yearly record and then that was changing, but here if you see that between this year 1278 to 1360, it almost sort of stabilize the in inclination was not doing, but again early here we see a sharp increase of the inclination then there was a stability, but the inclination was changing.

So, we see that we have a complete record of the direction of the inclination and in which degree the inclination. So, you see that inclination was actually quite a lot and in terms of the degree and it was going more towards the southern side and this is actually this abrupt increase of the inclination when a definite value of the height at been attained is a clear sign of an impending phenomena of instability in the structure of equilibrium which is called leaning instability and this is actually the phenomena which caused the problem.

(Refer Slide Time: 11:19)



And this we can see that if you can see here that this is the Catino where this portion that you see that how much sort of it has been within the ground. So, that inclination was quite clear.

So, if you see that the monitoring actually happened when there was a realisation that there was a inclination was still there and it was changing the degree, there was a recorded study for there and monitoring of the rotation which happen. So, now, we can see that it increases more than the rotation of the foundation implying that there is steady deformation of the tower body and the long term steady trend is marked by two major perturbation; that means, something was happened to the structure and which lead to some sort of perturbation it was not happening at an uniform rate let us see what are these perturbation which happened.

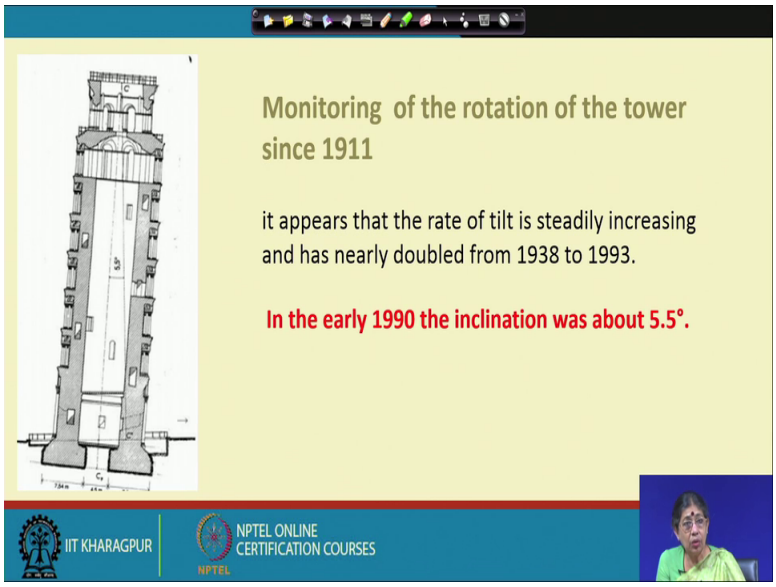
In nineteen thirty five it is caused by a cement grouting into the foundation body and the soil surrounding. So, people thought that if sort of a consolated the soil around that and the foundation probably it can keep some strength to the thing. So, it was and also it was down because there is a lot of inflow of the water. So, specially this was done to not only to strengthen, but also carried out to prevent the inflow of the water.

In early 1970, it was related to the pumping of the water from the deep aquifers. Now the soil is on a different layers and there is a underground water level. So, when there is a pumping happens to that; taking out the water, what happens? The groundwater level

changes and that changes the structure of the soil structure and including. So, what happened that when the pumping of the water was happening because of the development are there around that area from the deep aquifers, it induce subsistence from all the Pisa plain. So, it was a greater area which is being affected by this change in the water level it is not only localised it was a much larger problem.

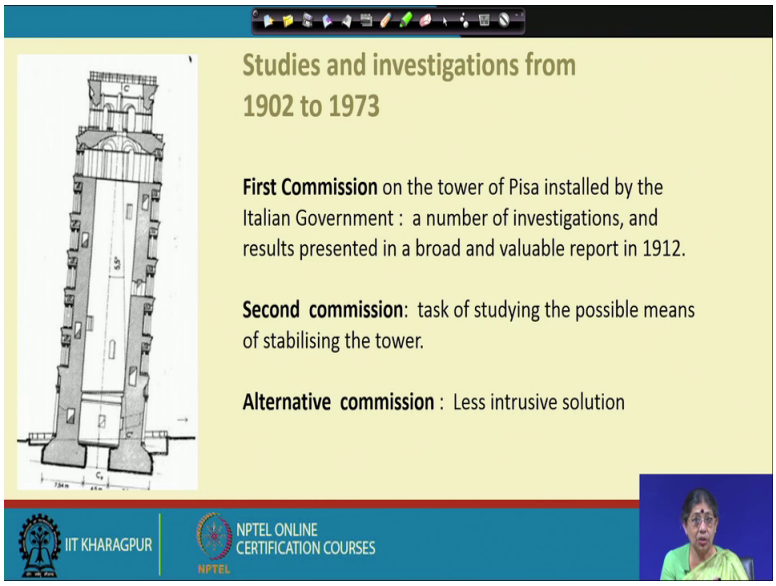
So, what was decided when it was realised during the monitoring process the closure of a number of wells. So, that the water cannot be extracted in the vicinity of the tower stop the increase of the rate of the tilt. So, there was some sort of a positive state which has happened that when they realise that the taking of the water was creating a change in the water level and that was creating the subsistence. So, there was an instruction or policy decision which really has at least to stop the increase of the rate of the tilt.

(Refer Slide Time: 14:02)



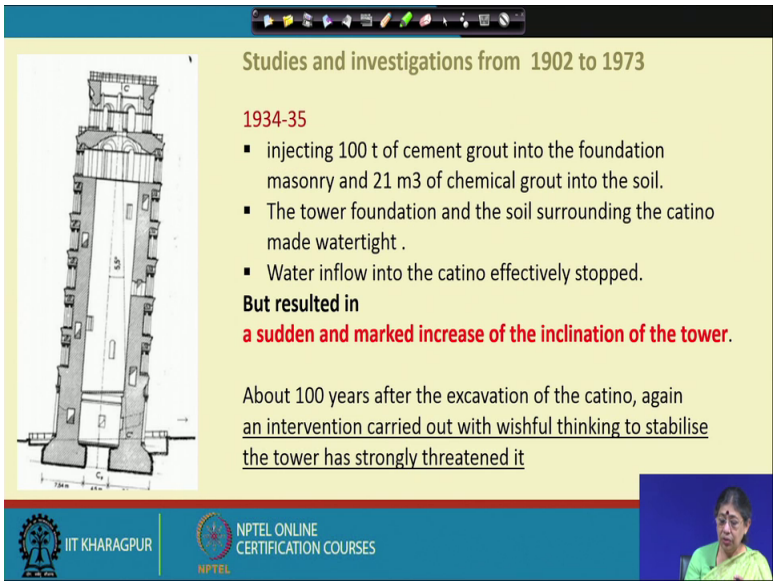
It appears that the rate of tilt is steadily increasing as not nearly double from 1938 to 1930; 1993. So, in the early 1990, the inclination was about 5.5 degree quite a lot.

(Refer Slide Time: 14:20)



Now, so, different studies were taken by the government of Italy to understand that now between 1902 to 1973 lots of commissions were done by the government to study that what is the reason and what is happening. So, at least some sort of a recorded monitoring and other things happen. So, let us see what are this commission and what are the basic things they did the first commission on the tower of Pisa was installed by the Italian government, a number of investigation happened and the results presented in a broad and valuable report in 1912 second commission also came this task was basically studying the possible means of stabilizing the tower there was also an alternative commission which try to talk about or their task was basically to find less intrusive solution. So, which can stopped and remember, the word intrusive solution that which should not really be very interfering with the structure 1934 to 1935.

(Refer Slide Time: 15:22)

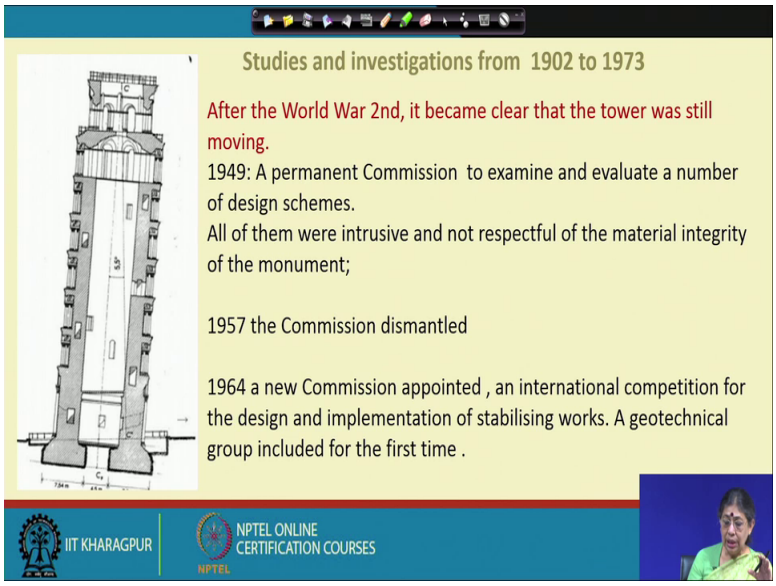


So, because of that hundred tons cement grout which I mentioned earlier and the chemical grout was done. So, it is basically consolidation which happened to in the ground.

The tower foundation and the soil surrounding, the Catino was made watertight because so that there is no water infiltration which is happening, there water inflow into the Catino was effect, there was a time when the water have to be pumped out of the Catino because of the water infiltration. So, actually that really stopped, but what is happening, but it resulted in a sudden and marked increase of the inclination of the tower. So, when this was happen that the change; the water inflame infiltration within the basement of the Catino that it actually change the rate of it.

So, about 100 years after the excavation of the Catino again and intervention so that is why the line what we said that the rate and other thing, the curve we saw that it was not uniform it was changing. So, suddenly an intervention carried out with it was the possible, it was a visual thinking, but which was the thought that it will stabilize the tower it actually threatened it.

(Refer Slide Time: 16:39)

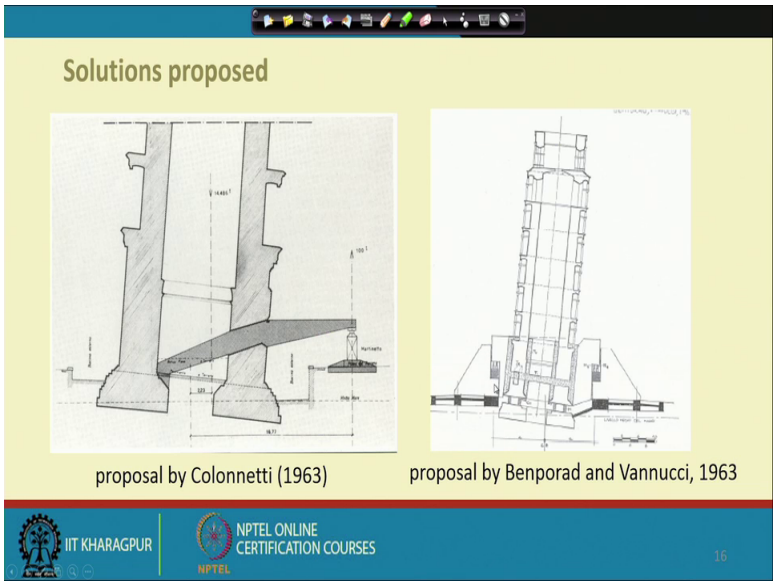


So, there was a war in between the Second World War happen and it after the Second World War the two wars were there. So, there was some sort of disturbance and some sort of not so much of attention was given, but. So, it became clear after the Second World War the tower was still moving.

In nineteen forty nine there is another permanent commission to examine and evaluate a number of design scheme that what can be done to that and all of them the design scheme which happen there were very intrusive and they did not because the major concern that time was to strengthen the structure. So, that it does not fall or does not collapse. So, most of case design solution which came will have a look that were intrusive and not respectful for the material integrity of the monument 1957; 7 the commission was dismantled and 1964, a new commission was appointed and international competition for the design and implementation of stabilizing work was the major task of this commission, but what is to be noted is that in this commission a geotechnical group inc was included for the first time.

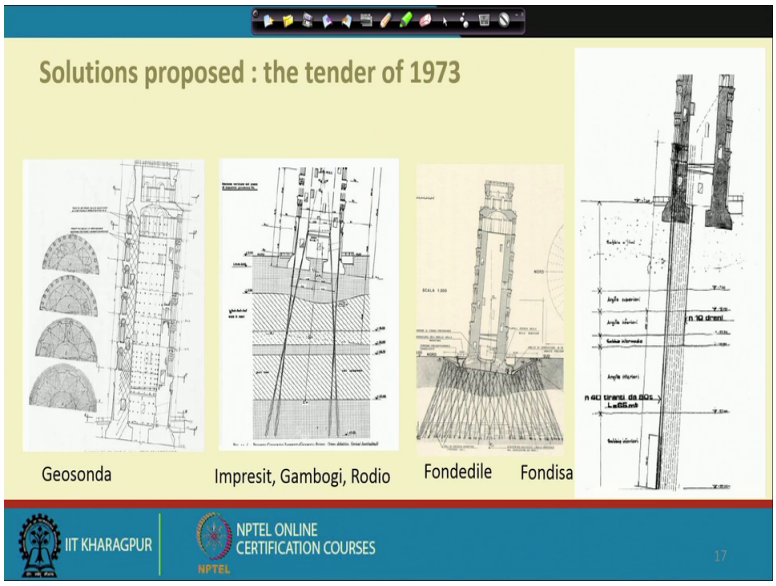
So, it was not only the structure, it realization was there that it has to be something to do with the soil and the geotechnical characteristics of the soil which has to be also taken into consideration. So, this is one of the very positive state.

(Refer Slide Time: 18:10)



Now, some of the solution proposed that during that time, let us see some of the solution which came because of this commission or because of the international commission and other thing let us see let us see in this one which was a proposal in 1963, let us see what is being done here. So, what they are trying to do they put another sort of a structures support there and through that they are trying to sort of rest there. So, sort of an anchoring so that it is sort of a thrust which is there in the support which should not be tilt because, but you can make out that how much it is intrusive solution, this one as you can make out that I mean this is sort of a propping out, it is trying to put some structures around this, it was sort of a propping up the structure so that it does not fall.

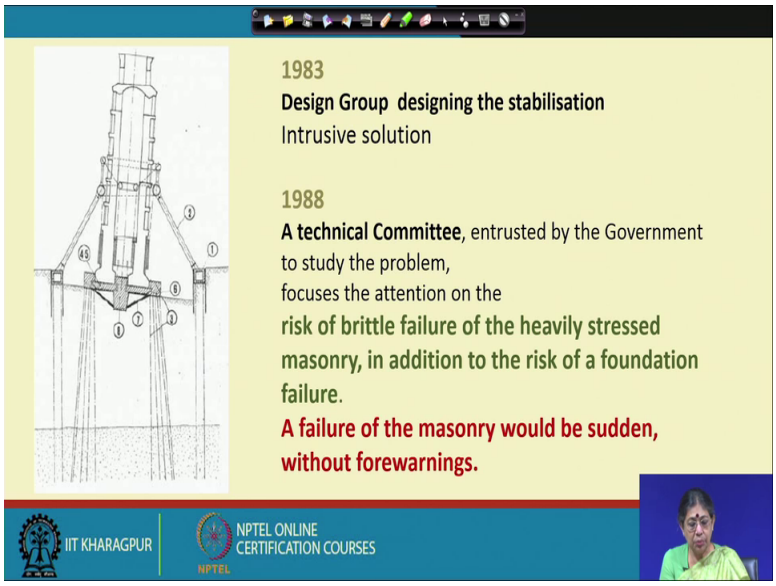
(Refer Slide Time: 19:05)



In this case, you can this because of the international competition, it happen that each and every layer of the tower they are trying to sort of a strengthen and the structure in subsequently in all the layers through some sort of a cross reinforcement by the stitching and this one, it was an piling under the which they called cross piling under that. So, that it was trying to go very deep into the soil and try to set settle or strengthen the structure, this you can see that there is a the entire under the foundation of the solve their trying to sort of a cross piling.

So, that it strengthens the structure and then it was another one which they are trying to take the piling only on one of the side. So, that it does not. So, all of this which one of this was structure solution came for very well known structural engineers and groups and were almost all of them were very intrusive solution fortunately, none of them were accepted by the commission there though they are almost close to accepting some of the solution, but fortunately this none of this was accepted and came to the final sort of awarding the tender. So, non no contract was awarded.

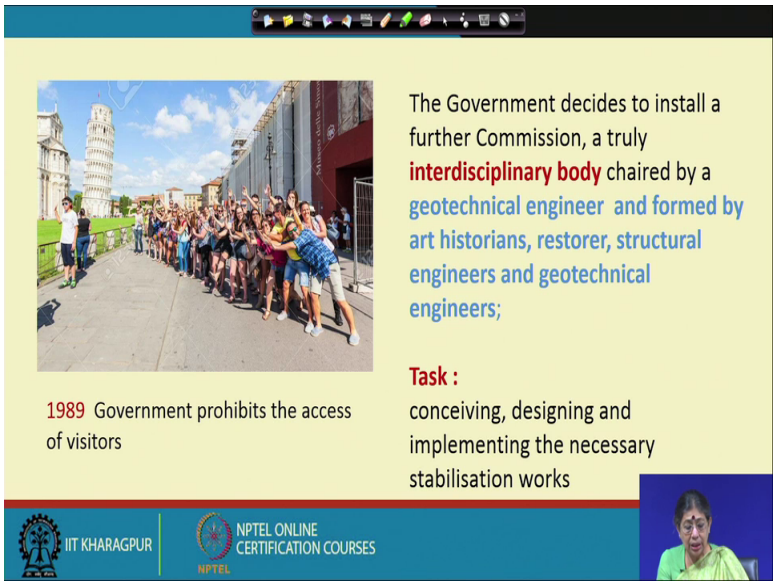
(Refer Slide Time: 20:34)



In 1983, a design group designing the stabilize stabilization did another intrusive solution as late as nineteen eighty three. So, let us see, what they have done here. So, they have also as you can see here is that that they have put a sort of this type of stabilization and their taking it down to the pier and there also putting a and they need to the foundation and their giving the file shared. So, this type of structure solution came and it would out visible that this person intrusive solution which they thought that will be working quite well.

Now, finally, in 1988, a technical committee interested by the government was there to study the problem and it sort of the task was there, it focuses the attention on the risk of the brittle failure of the heavily stressed masonry in addition to the risk of the foundation failure. So, that was the major intention of 1998 solution problem and it was realised the failure of the masonry would be sudden and without any forewarding and nothing can be done there.

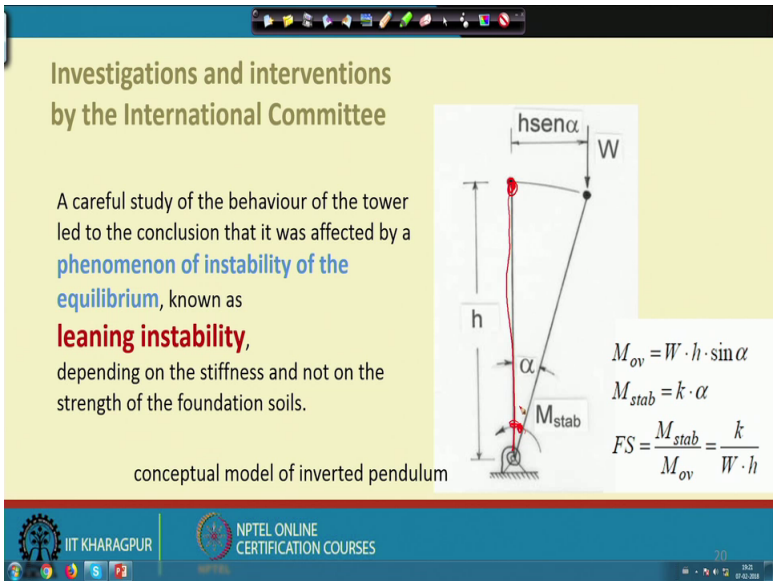
(Refer Slide Time: 21:53)



So, what happened not only the that it can collapse at any moment without any sort of warning fore warning, it is also became a constant for everybody because it is a major tourist attraction place a lot of visitors come there from all over the world for the safety of the visitor became a very concerned everybody become concerned about that became a major issue.

So, in 1989, the government prohibits that access of the visitors, but there was a lot of protest from the visitors, but it had to be done the government then finally, decide to install a father commission a truly interdisciplinary one that is to be saying that these also not only took the structural engineer geotechnical engineer, it was chaired by a geotechnical engineer and it had the art historian the restorer the structural engineer and the geotechnical engineer. So, it was really in a true sense a multi disciplinary committee with all the experts and the task was conceived and design and implement the necessary stabilization product.

(Refer Slide Time: 23:01)



So, what they did was that already there a lot a studies there, there is a record, there is a lot of thought which went behind that. So, a careful study of the behaviour of the tower led to the conclusion that it is affected by the phenomena of instability of the equilibrium as I have already mentioned known as the leaning instability let us see, what is this leaning instability and what is the realisation happened to the committee, it was like the and it was it also realise that it dependent on the stiffness and not on the strength of the foundation soil because. So, for all the solution which came just trying to strengthen the foundation is now they realise, it is depending on the stiffness and this was something which can be realise if you try to understand the phenomena of an inverted pendulum.

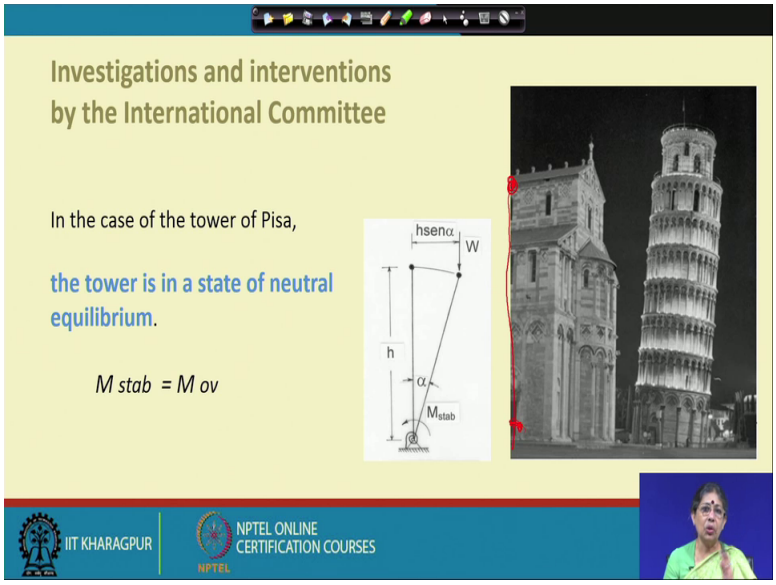
Let us see when a pendulum happens what is that there is a sort of vertical body I mean generally we see the pendulum their weight and there is a mass on the top of it ok. So, what happened there is moments one is that the movement of overturning and movement of stability know these actually creates a sort of a equilibrium. So, when it is in equilibrium; that means, the movement of stability the ratio and divided by the moment of the overturned in the movement of stability is more.

So, what happened like a pendulum it go, but it will come back to its original position, but when these two are equal when the movement of stability of the moment of stability in the movement of overturning they are equal, then what happened it will go and it will stay in that position, but what happens when the movement of overturning is more than

the movement of stability then it what happen it will collapse. So, these are the three scenarios which can happen and, but it was not the pendulum which is happening that way. So, it is almost a hinge and it was trying to. So, if it is equal then it will go and then it will come back if it is this is more, it will come back, but if its equal then stay in that position.

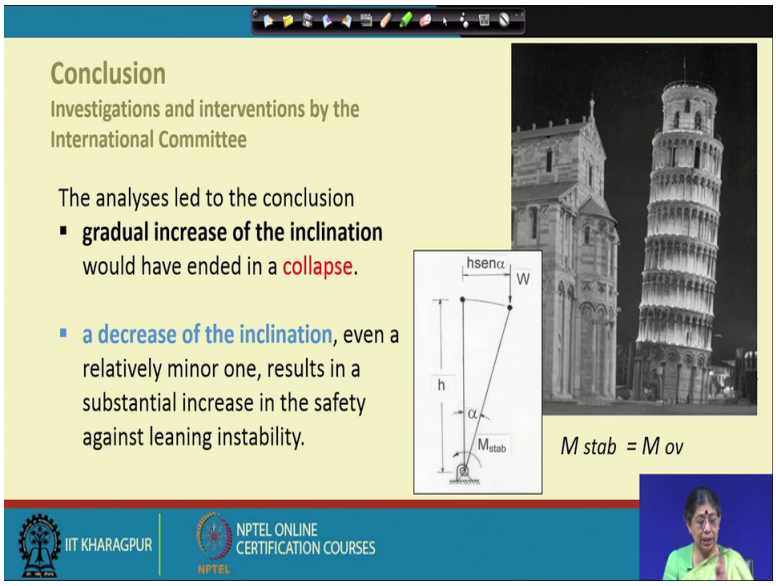
If the movement of overturning is more than it will fall and that depends also on that angle that depends on that angle. So, this angle is very important and that was realise that time that beyond a certain angle this will become more.

(Refer Slide Time: 25:37)



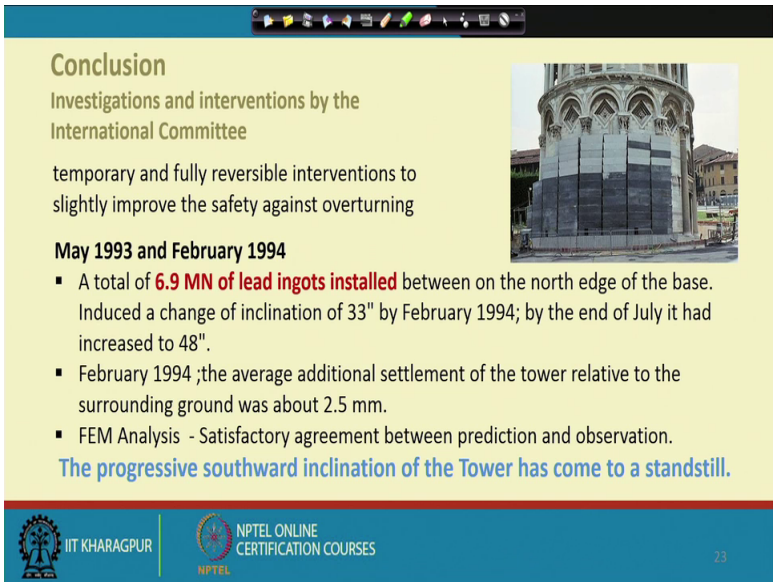
So, in the case of Pisa tower, this is what is happening moment of stability is equal to the movement of overturning and that is why it is stayed in that position, but the moment it will increase then it will not be possible to take it back. So, that was that was realise that this behaviour actually lead to what can be done about that.

(Refer Slide Time: 26:01)



So, analysis lead to the conclusion that a gradual increase in the inclination would have ended in a collapse a decrease of the inclination even a relatively minor one result in a substantial increase in the safety against the leaning instability this is very I mean important realisation which happened because the studying the behaviour of the tower and equating with that the concept of the leaning instability.

(Refer Slide Time: 26:38)



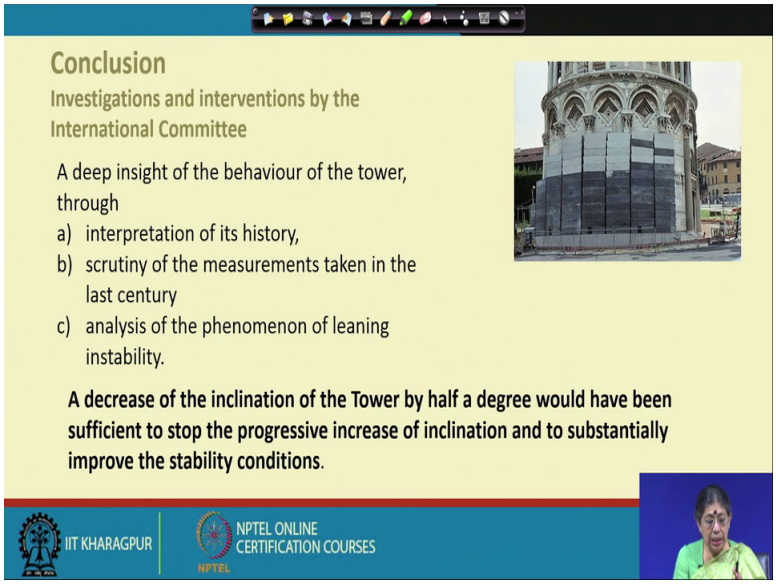
So, what was that? So, now, what can be done? So, first is to reduce that angle and how do you reduce the angle and how they reduce the angle. So, some sort of a temporary

measures you taken a lot of finite element more than a analysis structures modelling the gravity analysis were done by this structural engineers and it was saying that some sort of a thing which is temporary and fully reversible intervention to slightly improve in the safety against the overturning this has to be what done. So, between may 1993 and February 1994, a total of 6.9 metric Newton of lead inverse was place there on the tower.

So, it was creative on one side of the tower and another side. So, it was creating a load on that side of the structure because it was leaning on the south side and by the by the end of the July, it is found that there was a change in the inclination and it is improving and then the average additional settlement of the tower relative to the surrounding ground was that time was 2.5 mille metre.

So, that temporary solution by putting the lead ingots on one side of the tower so, found that it was improving the situation . So, there is finite element more than analysis first that and there was satisfactory agreement between the prediction and observation. So, there was a scientific way and how it was done there and they found that it can lead to some sort of a solution the progressive southward inclination of the tower because of this putting the lead in store lead ingots actually the tower has come to a standstill; that means, the further inclination was stopped because of the temporary measure and putting an extra weight on the other side.

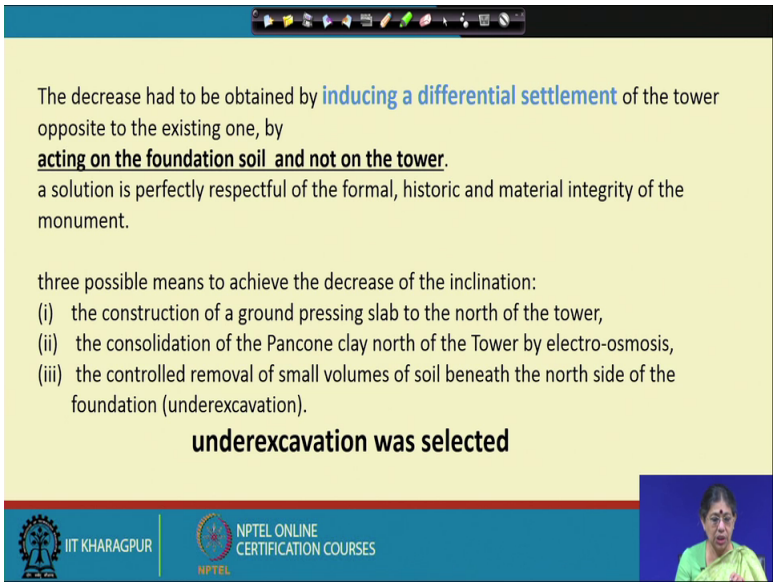
(Refer Slide Time: 28:34)



So, deep inside of the behaviour of the tower through an interpretation of the history we must understand that it actually was a combination not only of the structure solution, it was combination of the interpretation of the history and all the records the security scrutiny of the measurement taken in the last century the records were available and the analysis of the phenomenon of the leaning instability that what we explain just now; these all three actually give a realisation of the behaviour tower and it was felt and realise a decrease of the inclination of the tower even by a half a degree would have been sufficient to stop the progressive increase of inclination and to substantially improve the stability conditions and this was a very good stay which was realise.

And now this temporary solution which has taken had to be translated into a permanent solution and how it can be done.

(Refer Slide Time: 29:29)

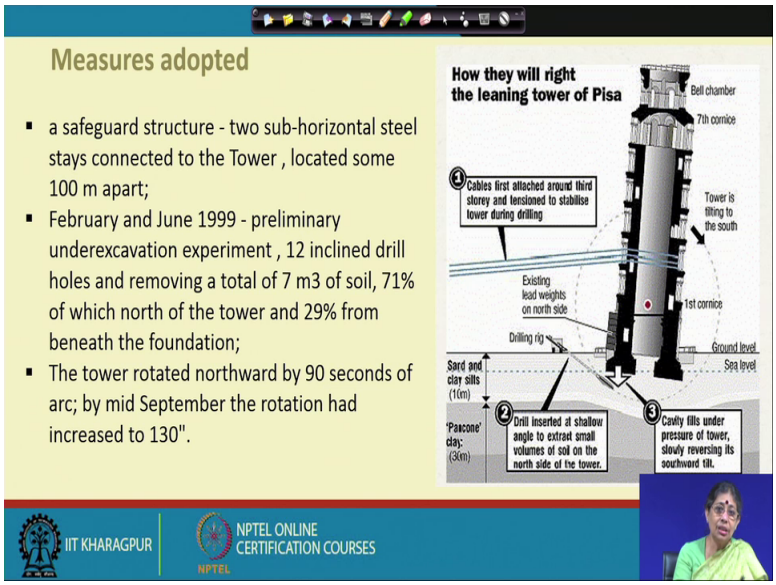


This the its quite simple it use to induce a differential settlement of the tower to take it to the opposite direction and how do you take this differential settlement acting on the foundation soil and not on the tower it really did not need any intervention of the tower itself, the solution is perfectly respective respectful of the formal historic and material integrity of the monument. So, this was realise and what are the three possible means.

So, one was the construction of a ground pressing slab to the north of the tower. So, that on that tower because we have to give an a extra load the consolidation of the clay north of the tower by electro osmosis this is also an excepted methodology the control removal

of small volumes of the soil beneath the north side of the foundation no same meaning, but taking out the soil extracting the soil from the north side. So, that it starts again a inclining towards that. So, finally, is under excavation that is taking the soil from the foundation of the north side, this was selected as a method.

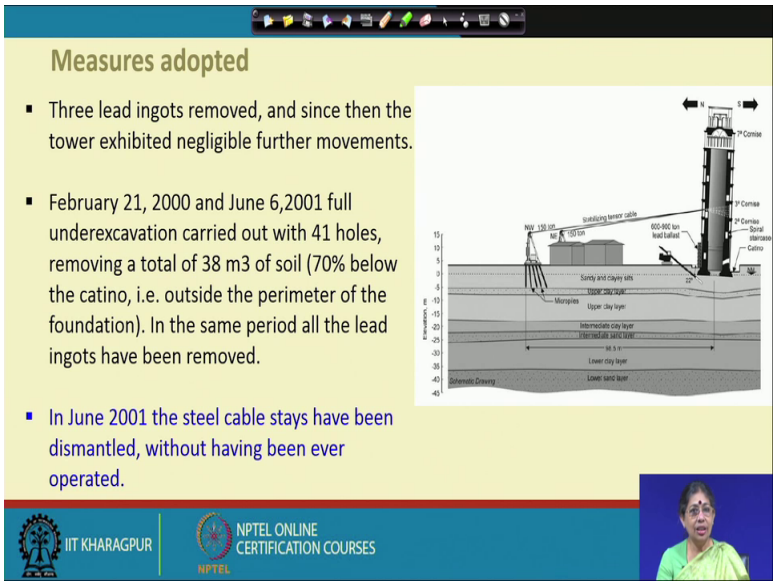
(Refer Slide Time: 30:40)



And for that what was done is that this is what actually done the on the two sides of that it was the stages were put up there and. So, that there was a some tie was there and through the dealing process the soil was extracted and as I say the safe guard structure was put up if the horizontal stay on the two sides of the tower and February and June 1999, preliminary under excavation happened twelve inclined drill was there and removing a total of 7 cubic metre of soil 70 percent of which was the north of the tower and 25-29 percent was from beneath the foundation.

The tower rotated northwards by 90 seconds of the arc by mid Sep by 7 September, the rotation had increased to 100 and so, it by inducing the settlement the inclination was sort of changing.

(Refer Slide Time: 31:34)



So, this is some of the cases as you can see the stages there which sort of holding that in case something happened there were the two stage of two sides and you can see the soil structure there and the lead ingots were gradually remove and this is how the drilling was happening to take a excavative soil.

So, the first it was done in a face manner the three lead ingots first remove and since then the tower exhibited negligible further movements and then in 2001, and 2000 and 2001, the full under excavation was carried out in an sufficient amount of soil which was calculated and which was a done through the modelling and structure analysis, it was taken out outside the parameter of the foundation in the same period all the lead ingots have been removed.

In June 2001, the steel cable stays have been dismantled; it was there so that something in case of eventuality if something happen. So, the stays were taking down without having been ever operated. So, it was not there. So, that was that after that there was no sort of an inclination and happen is no further till and as a result what will happen is that you have been able to say tower which is favourite of the tourist all over the world you see they come and try to see that is still leaning, but the thing is that by understanding the phenomena which was happening there the problem have been solved.

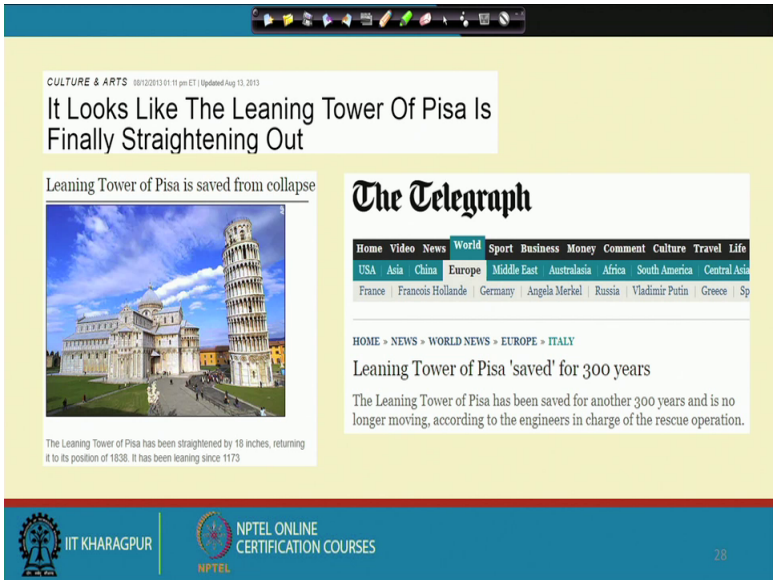
What is really interesting to see in these particular case that there has been a scientific understanding there has been a recording there has been a multidisciplinary team and

fortunately all these intrusive things did not happen there, it was diagnoses proper diagnosis of the problem and the solution which can take up it is not very complicated, but that understanding was very much required.

And of course, there is scientific investigation and nowadays which was probably not there 200 years back or 100 years back, a lot of modelling is possible and to see that what is the what is the likely impact which has been happened there if you look at the history of the monitoring recording and the other it look that I mean it could have been a disaster by either it could have collapsed or just imagine that when all the structure or structure solution we have say that it would have happened we did not have seen the leaning tower of Pisa what we see today.

But fortunately by understanding the phenomena the proper diagnosis proper understanding and multidisciplinary team and the recording, it is save the leaning tower of Pisa and this is the value of the or important significance of the proper diagnosis of the problem so that proper intervention measure can be there.

(Refer Slide Time: 34:42)



And that is why we know that all the news people all over the world are very happy they said it looks like a leaning tower of Pisa is finally, straightening out the leaning tower of Pisa saved for three hundred years or leaning tower of Pisa is safe from the collapse it was just it was the rotation understanding the phenomena and induce settlement and so, the rotation changes and by taking out the soil from another thing. So, that this was what

was done not only at one go, but over stages in a very careful way and by a conscious decision and study and investigation by a very multidisciplinary team to see.

And that respectful understanding that what is really happening is a very important part of that. So, that is why we say that investigation diagnosis research documentation and recording the over the years for a historical structure and how it can lead to saving the structure for perpetuity next lecture, we will talk about another very interesting case.

Thank you.