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Use of Steel in Hydraulic Structures, Fixed Plants.

Anwendung des Stahles im Wasserbau, feste Anlagen.

Application de l'acier en construction hydraulique, installations fixes.

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To deal with the theme "Steel in hydraulic structures" at an international congress in connection with bridge building and structural engineering may at first seem rather strange. But when one considers that steel as a building material plays an important part in the foundations of bridges and other structures, it is comprehensible that the Congress should deal also with this subject. In the first place there are the fixed structures mentioned in my report, which stand in direct relationship to bridges and other structures, i. e. steel sheet piling as a means now universally adopted for constructing the foundations of piers, etc., and then there are also the steel piles next described, as well as other types of foundations. But since the experience made with supporting structures of steel is considerably greater and more interesting than the observations made on piers, such supporting structures will often be referred to in what follows. But it may be mentioned that the results of observations and experience with such structures may at once be applied to piers and other foundation work made of steel.

1) The physical and chemical behaviour of steel as a building material.

Since wood and reinforced concrete do not in all cases possess the physical and chemical resistance required by building materials when used in structures in water, it was only with hesitation that the adoption of steel for such work was started about 30 years ago in Germany. Its use has been extending more and more since 1920. It was considered that the introduction of steel would diminish to a great degree the attacks to which building material was exposed, and that a material had been introduced into hydraulic structures which would prove more suitable than any other in this respect. However, the extent to which steel is also liable to physical and chemical attacks in air, in alternating air and water, in water itself, and in the ground, was not overlooked.

Now that the experience of nearly a generation is available, it is time to compare the theoretical considerations and the experience gained in research stations with the observations made on structures executed, and thereby draw conclusions concering the suitability of adopting this material, and as to how it can be improved. The difficulty in the stipulated requirements consists, also for steel, in the material having in most cases to pass through four different zones, each of which has its own particular physical and chemical characteristics tending to attack the material, and further that different kinds of steel behave differently according to the composition of the soil and of the water. But it is demanded that the building material should be as far as possible equally resistant in all the zones (air, alternating air and water, water and soil). Observations, however, show that this aim has not been attained up to the present. It appears to be as yet fundmentally impossible to get one and the same material to be absolutely suitable for all the different conditions in the four zones.

In the air, it is principally oxygen which acts on the material, but in some cases there are also industrial fumes and atmospheric influences. The attacks on the building material are mainly take the form of corrosion.

With alternating air and water, there is more severe corrosion because of the considerably greater amount of moisture and the corrosive substances present in the free water. By means of alternating wetting and drying and by wave action, the oxygen is communicated to the material to a greater degree and the chemical reaction is thereby greatly intensified. In addition there are mechanical damage and stressing, through traffic, ice, etc., etc.

The difference between alternating wetting and drying in sea water and in fresh water should be noted. In sea water this causes more extensive destruction, since it takes place in continuous short alternations (tides); the wave action is also more intense, and the salt contained in the sea water has an unfavourable effect. In hot regions, the warming of the water and of the material plays a further important part.

It ought to be expected that the destruction of the material under water would be less. But this is in general only the case down from a certain depth below the water line downwards. In fact, the first 1—2 m below the alternating air and water zone often displays even more severe destruction than in the part above; and here again this action is more intense in hot regions than in temperate ones.

In the soil the durability of building material depends on the corrosive properties of the soil and sub-soil water. There are kinds of soil in which the material is practically not attacked at all. It may also happen, however, that destruction occurs which it would hardly have been possible to determine beforehand, since there is seldom any opportunity of withdrawing sheet piling again after any length of time.

2) The causes of damage to steel and their obviation.

Mechanical damage will also occur to steel structural work driven into the ground, such as piles and sheet piling, if the cross-sections are not chosen properly in relation to the density of the soil and to the desired depth to which the material has to be rammed. In such cases damage occurs at the top and bottom of these structural parts, and this may lead to the continuity of the wall being destroyed. Whilst the parts of the piles and sheet piling underground remain invisible to the eye, the damage at the top may be restified by cutting away with the burner. But this remedy can be repeated only up to a certain limit, otherwise the required depth of ramming cannot be obtained. The part played by the ramming in causing damage to the steel in structures in earth and water may be considerably more extensive than the damage caused under ultimate service conditions, if the fundamental principle mentioned above is not observed.

Under the heading of mechanical damage comes wear in consequence of the motion of the water. Steel structures erected in stationary water will have a much longer life than those in running water, where the current carries mud and floating matter along with it. For example, damage will soon be caused by the action of quartz sand. Cases are known to us, where the most exposed parts of a steel sheet piling have been cut through at ground level within seven years. Abrasion by sand is certainly the principle cause of mechanical damage to the steel; on the other hand, the stressing caused by ice and wave action must be considered as slight.

Wear and tear from shipping traffic, from being knocked by vessels when arriving and departing, depends to a very great degree on the amount of deflection caused in the structure in the service condition and on the protection afforded by fenders, etc. No case is known, where such damaged has been so great as to necessitate renewal of the structure or of any of its parts. Nevertheless the stressing thus caused should be clearly recognised beforehand, and the design arranged in such a way that softer materials, for example wood, and bundles of cane or faggots, are adopted as fenders to absorb any great forces which might cause damage.

Damage from weather (rain and great differences in temperature) come less into consideration in our regions.

The durability of steel structures is impaired much more by chemical action, especially by corrosion in the separate zones. The experiences hitherto made in Germany differ so much from each other, that it has not yet been found possible to reduce all phenomena to one common denominator, although the question of corrosion has been very fully treated at meetings and in publications. It is therefore unnecessary for me to go further into this matter; I would, however, point out that, because of corrosion, it is to-day still impossible to foretell the life of a steel structure with certainty, since the figures with regard to corrosion which have occasionally been made available by different makers show very great variations. That is not surprising, since the structures have been observed under very different conditions, and the amount of corrosion depends to a very great degree on the composition of the water, air and soil, and also on the temperature. There are districts in Germany which, for this reason, cause quick destruction of the steel, whilst in other districts the life of the steel is many times longer, although there are possibly no differences in the composition of the water which are at all visible or can be chemically determined.

I may in this connection refer to the experience made in connection with continuous steel walls, i. e. that they are less liable to corrosion than separate posts standing in the water. For example, at a place on the North Sea coast, destruction of the steel in such posts took place within 20 years, whilst a wall near them, of the same cross-section, though it showed somewhat severe corrosion, was not damaged to such an extent as to render it unserviceable.

Undoubtedly the composition of the steel is of essential importance, but to what extent has not yet been fully explained.

Based on investigations made by various authorities, the *lowest* limit of the life of steel poles and steel sheet piling subjected to corrosion, under normal circumstances, is estimated as being at least 60 years, a figure which must be considered as amply sufficient in very respect in comparison with the economical service life of such structures. I may, however, also remark that the upper estimated limit of life extends to several hundred years, a figure which of course cannot be scientifically proved.

Tests mode on a structure for shipping traffic at the mouth of the Weser showed that the extent of corroding of the sheet piling, eight years after erection, was 0.2 mm.

One type of destruction which must not be regarded too lightly is electrolysis. A preliminary condition for causing electrolytic action in steel structures is the use; in the presence of moisture, of materials of different composition, in certain cases even the use of different kinds of steel, and not only different metals, may suffice to set up electrolysis. A great deal of work will have been done in future in this connection in order to guard against damage.

As already mentioned in the introduction to this paper, it is possible to give only general particulars with regard to the frequency with which damage occurs. However, the seat of the trouble will generally be found either in the zone subjected to alternating air and water or a few metres below it. The most common and the most dangerous phenomena leading to damage are corrosion and defects caused by the work of ramming.

Sources of greater damage may easily be deduced from what has already been said. It has up to the present not been found possible to control them sufficiently by adopting any particular precautions against them. They must first of all be accepted as inevitable, and the endeavours of the engineer must be directed to trying to reduce the damage by other methods.

Of significance here is first of all the presence or absence of rolling mill scale. This scale is an unavoidable drawback of the rolling process, since it has no longer any reliable connection with the steel beneath it. It therefore tends to flake off easily as soon as a wedge enters between it and the material. The scale can be removed by sand blasting. Nevertheless, in hydraulic engineering, one is in most cases content to leave the scale on the material.

The precautions which can be taken against the damages mentioned above comprise a particular composition for the steel, external painting, metallic coatings, encasing in concrete, and appropriate choice of external shapes. The most preferable method of all is to keep to the course hitherto pursued, i. e. improvement of the composition of the material. Even if the addition of copper has not everywhere fulfilled the expectations based on laboratory tests, it is a fact that in many cases a properly proportioned admixture has made the steel more resistant; this is an advantage which has proved extremely favourable at least when ramming. The experience made with high-grade steels in actual service certainly does not point to the absolute suitability of these admixtures in every case.

The experience made in Germany and also in England is far from being uniform. Whilst it was found in England that ordinary steel corroded most severely when fully immersed in very salt water and least severely when fully immersed in brackish water, chromium steel corrodes easier above water than under it. On the whole, however, the latter steel proved to be superior. At another place, on the other hand, very severe local corrosion was found in chromium-nickel steel, and experience showed that the addition of copper led to no improvement.

The conclusion which can be drawn from the experience made in England tends to show that carbon steel is apparently superior in the air, whilst wrought iron has proved to have a greater resistance in alternating water and air and also under water. It is rather surprising that an addition of copper gives greater resistance against corrosion in the air and in fresh water, but not against corrosion in alternating water and air, or under water in the sea. The same may be stated with regard to chromium steel and nickel steel.

The effects of electrolysis when different kinds of steel are brought into contact in sea water are rather interesting. The phenomena which occur protect St 37 at the expense of wrought iron, and protect chromium or nickel steel at the expense of carbon steel. The material of higher grade is consequently protected at the expense of the material of simpler composition.

External painting to protect steel structures[1] can really be adopted only for parts exposed to the air. For parts in the ground, which have to be pressed in by force, painting should not be adopted, since it will certainly become damaged to a certain extent during ramming operations. It should also be clearly understood that an external coat of paint requires continual maintenance. The expenses in connection with this work are to be considered in connection with the economical service life of the structure. There is not a single kind of paint at present on the market which will give complete protection unless it is also continually attended to and renewed. If a paint manufacturer asserts that it is possible to bring a coat of paint undamaged into the subsoil, even if the part in question is rammed through sharp sand, this can be regarded only as a purely theoretical assumption.

On the other hand, metallic coatings (zinc or lead) are extremely valuable and prevent the occurrance of wasting through corrosion. But since these coatings are very expensive, they come into question only for certain parts, such as ladders, mooring bitts and rings, corner protecting irons, etc., but not for sheet piling or piles.

Also giving the steel piles and sheet piling a light casing of concrete does not offer any durable protection, since, as is well known, it is difficult to get concrete to adhere to large iron surfaces.

[1] Cf. also the remarks of Ministerialrat *Burkowitz.*

The external shape of the walls may contribute greatly towards diminishing the effect of wave action, currents, and abrasion by sand. Profiles have therefore been designed which ensure the surface remaining as smooth as possible, in order to prevent the formation of eddies and thereby the development of friction surfaces.

The question now arises, to what extent the above-mentioned precautions for reducing damage to the material allow existing steel sections to be set at full value in the calculations, i. e. to what extent it is justifiable when designing the work to base calculations on the existing dimensions of the steel parts. With regard to this, no uniform rule can be given. It will not always be possible to do without allowances for corrosion of the structure, especially if experience has shown that steel is liable to be severely attacked in the district in question. In Germany such districts hitherto found are happily only at isolated places, particularly on the coast. In all other cases there should, in my opinion, be no reason why the steel used as a structural material should be calculated with reduced stresses, in order thereby to give the steel an apparently longer life. I would even go so far as to describe this as an unnecessary waste of material.

3) Development in the adoption of steel in hydraulic engineering.

When it is considered that thirty years ago steel was principally used in Germany only for certain equipment of navigation service structures, such as bollards, ladders, mooring bitts and rings, edge protectors, anchors, etc., etc., it is remarkable that to-day it has been adopted for preventing the movement of earth by means of sheet piling to such an extent that more steel than wood or reinforced concrete is now used for such structures. The steel production for hydraulic engineering purposes in Germany is now estimated at more than 200,000 tons per annum in round figures. The figures for the output of a large German steel works give an idea of the increasing use of steel in hydraulic engineering (based on value in Marks):

1910: 100	1925: 196	1928: 1183	1932: 373
1915: 130	1927: 855	1930: 790	1934: 1150

During the last five years, steel piles particularly have been slowly but surely becoming more widely adopted and, in my opinion, their use will still continue to extend and to decrease the use of the two other materials, wood and reinforced concrete, unless reinforced concrete should also strike out in new directions for this purpose.

4) The possibilities of adopting steel.

The bulk of the steel used under present-day conditions in foundation work and hydraulic engineering is to be found in sheet piling structures, which are still being more and more adopted, since they are employed not only for finished structures, but also for temporary constructional work, for example for supporting foundation pits. They come into question not only with pile foundations, but also with solid foundation work (sinking with compressed air and well foundations).

The advantages of sheet piling lie in its economy and convenience, and in the speed with which it can be erected. The ramming makes a saving in excavation work and water retention. On the other hand, special demands are certainly made on steel for sheet piling, and they may be briefly defined as high values for yield point and elongation, high resistance to notching tests, great resistance to corrosion and to abrasion. These values vary with respect to each other in the different kinds of steel on the market, but can be developed in relation to each other in one and the same kind of steel. The various manufacturers of sheet piling supply special steels which may be described as all essentially similiar, and certainly as equally good.

These high-tensile steels will, however, be adopted only in exceptional cases; in general it will be found sufficient to use standard structural steel. When the latter is used, the profiles will be of greater cross-section than when high-tensile steels with greater permissible stresses are used; consequently the sheet piling structure will have less tendency to bend. Further, the greater liability to corrosion will in many cases be partly compensated, since with the greater quantity of steel in the structure a wastage of 1—2 mm will weaken the section less in percentage than would be the case with the thin-walled sections made of high-tensile steel. In addition, a greater moment of inertia may be of advantage in long sheet-piling walls when ramming, since the stresses which occur when forcing it into the ground, especially forces tending to cause buckling and vibration, are then diminished. Often it will be found impossible to avoid using high-tensile steels, particularly if the material is to be subjected to indentation and also to great abrasion during ramming operations.

From what has been stated in the second section of this paper, it can be seen that the final word has not yet been spoken concerning the suitable composition of high-tensile steels. In addition, from the point of view of economy, it is not possible to give any definite, general ruling as to when normal steel or high-tensile steel is preferable.

The demands made on sheet piling are the following:

High section modulus with little weight, i. e. a high coefficient of quality. Little deflection, conditioned by large depth of cross-sections. Staunchness of the wall, which will be attained essentially by the form and position of the locking joints. Good guidance for the locking joint, and little tipping or twisting of the wall during ramming.

When the different sections used for sheet piling are compared, it will be found that by far the greater number are of the single-lock single-wall type. The single-lock two-wall type (box section) and the two-lock two-wall type (Peiner section) come into question only for structures of fairly large size, and these are becoming more and more common in consequence of the increasing traffic demands made during recent years.

Advantages of the corrugated section as compared with the two-wall sections are that it is more easily possible to obtain a good junction of the structural parts, and that it is easier to ram, since there is less soil to be displaced and obstacles may be rammed round to a certain extent. In structures such as coffer dams, which require to be very well strengthened and stiffened inwardly, an endeavour will be made to manage as far as possible with corrugated sections, unless it es desired to use single-wall coffer dams, which are statically more exactly calculable, or even the double-lock two-wall section which is certainly of advantage in such cases.

In recent years trials have also been made with welded sections of many different shapes which, with the high development of welding technique in Germany, are to be considered as just as good as the rolled sections from the point of view of construction and service. Whether they will become commonly used will depend on their economy. It is left to the steel makers to strike out in new directions in this respect.

Besides the demands made on the material and on the section there are finally the demands on the finished wall. The erection of hydraulic structure by sheet piling methods is limited by the fact that these allow only plain flat walls to be constructed, and then only if certain unavoidable deviations from the intended line are permitted. With this method of working, only walls can be provided in which small irregularities play no important part. Further, since the wall is quite flat from top to bottom and the later provision of any recessing is almost impossible, the structure will always be of a rough block-like character. In many cases a compromise may be found possible, by cutting the sheet piling through above the water line and adding a reinforced concrete construction, the shape of which can be of more elaborate design. Nevertheless, the sheet piling method of construction cannot be considered at all for structures which are intended to make any display of elaborate work externally.

As already mentioned, the extensive use of steel sheet piling in Germany shows that it has now been adopted for constructional work of many different kinds. There is no need to refer to them here individually. It should be mentioned that, based on past experience in executing structures, there is to-day no longer any difficulty in driving sheet piling walls, 30—35 m long, into the ground undamaged, if the requisite precautions are taken. With the Peiner sheet piling we have thicknesses of section which are theoretically sufficient for banks of any free height, unless it is preferred to adopt the proved design of single-lock sheet piling walls, for example steel coffer dams.

Trials made with transverse welded sheet piling in order to simplify transport to site, have also shown that these walls behave well when being rammed. Reference may also be made to the practice, first introduced by me, of strengthening single-lock sheet piling by welding-on a flat iron strip where the greatest moment of resistance is required. Eight years' service has not yet shown any drawbacks.

From the sheet piling methods of construction, in consequence of the necessity of supporting vertical loads through the sheet piling, the adoption of steel for piles has also developed, after their great serviceability for this purpose had been determined from loading tests made on single-lock and two-lock sheet piling. The demands made on the steel for piles are the same as those made on steel for sheet piling. The section of the steel pile must conform to the following requirements:

In piles brought into the ground not by ramming but by screwing, the section must be of such a shape that it provides the necessary supporting resistance corresponding to the required carrying capacity of the pile, and the piles must also be as little as possible liable to damage from stones or other obstacles encountered underground. This leads to certain requirements regarding the width and pitch of the screw thread. This type of steel pile has scarcely been adopted at all in Germany, since its success would be very doubtful with the conditions found in our soil. On the other hand it is to be more frequently found in out-of-the-way districts, for instance in the tropics, since it is difficult there to acquire modern building equipment.

In contrast to the screwed piles, the rammed piles have only been adopted in Germany in recent years. In this respect we are still at the beginning of a development, for the number of such piles used up to the present is still small. The sections of the driven piles must show great friction between the pile and the soil, but without thereby causing the resistance to ramming to become insuperably great. Further, the cross-section of the pile must be amply large, so that the carrying capacity may not be limited by the permissible stressing of the material. The section must have a moment of inertia sufficiently high and as far as possible the same in all directions, so that the necessary factor of safety exists both when the pile is being rammed and when it is in service. In order that the pile may, at least approximately, take up its intended position in the soil, the section must be sufficiently resistant to prevent bending underground during ramming operations.

With regard to the design of steel piles, two different procedures have been adopted. In one an endeavour is made to obtain the required carrying capacity of the pile not so much by the surface friction of soil on steel, as by a great point resistance, but then, because of the large circular or rectangular cross-section, considerable quantities of earth must be displaced, unless resort is had to "washing" the pile in, in spite of all the drawbacks this method entails.

In the other method an endeavour is made to obtain the carrying capacity in the first place through the friction of soil on soil, in that, when ramming, the soil is artificially pressed so firmly in between the flanges of the I-shaped pile, that this pressure is greater than the friction of soil on steel. These piles have the advantage that they are comparatively narrow in the lower part and displace the soil only to a small extent.

The first kind of pile is of tubular or of box-shaped section; they are rammed with or without earth filling or with artificial points. However, since the soil forces its way into the section after a short time, it is of no great importance for the resistance to ramming whether the pile is fitted below with a concrete plug or not. Fitting such a plug may therefore be described as superfluous and uneconomical.

The whole earth filling of the pile is only washed out afterwards and replaced by concrete, provided the water is of an exceptionally corrosive character. If the steel wastes away later, a concrete pile remains; if found advisable, iron can also be previously embedded in the concrete.

The open sections consist of T-beams without bulb (flat iron tips), which possess a comparatively low carrying capacity. For this reason, the double T-beams have been provided with a bulb which, when of the right length and in the right position, can greatly increase the carrying capacity of the piles in compression or in tension.

More suitable than double T-beams is the use of broad-flanged sections with or without bulb. If the Peiner sheet piling is used, piles are obtained by ramming separate units together, and within these piles the provision of bulbs is rendered superfluous, since the soil very quickly presses in between the separate flanges. In this case an intermediate construction between closed and open sections is obtained.

Further open sections are U or Z sheet piling, which can be rammed as separate units or with several set together. In this case a bulb has hitherto not been provided, since these cross-sections are used mostly when the vertical stressing is only a partial stressing, and the principal forces occur horizontally.

Welded beams have not yet made their appearance as steel piles. But there seems to be an extensive field open for their adoption here, since they are capable of being suited to the special requirements of the rammed pile much better than rolled sections.

The carrying capacity hitherto determined by tests on various kinds of steel piles is very high in comparison with wooden piles, and almost the same as for reinforced concrete piles. In this connection no great difference could be found between open and closed sections. The figures obtained from experience with compression piles vary between 80 and 120 tons, with a settling of 2—8 mm at the maximum for bulb section piles. Loading of Peiner double sheet piling in the wall gave a carrying capacity of about 300—350 tons with a settling of 15—20 mm. There is very little information available concerning tests on the resistance of tension piles, so that no conclusions can be formed from them regarding the tensile strength of steel piles. In Bremen 70 to 80 tons was found, with a permanent rise of 3 to 4 mm.

The adoption of steel piles to any great extent has hitherto been confined to the strengthening of quay walls in Hamburg and Bremen.

Experience has however shown that open piers should not be constructed with steel piles, since they offer too great surfaces for attack by corrosion. They should therefore be enclosed by sheet piling and surrounded by earth.

For a long time steel jackets for reinforced concrete piles have been used when the reinforced concrete pile must pass through ground which is liable to attack the material, and also in cases of special constructions, such as tube and press piles, where the tube is again withdrawn. No special demands are here made on the steel. There are no great innovations to be mentioned in this connection.

Steel is also adopted instead of reinforced concrete and masonry in well shafts when water and soil layers liable to attack the material have to be passed through when sinking. Nevertheless, the execution of well shafts in steel is very much rarer than execution in concrete.

In the same way steel caissons are not so widely used as those of reinforced concrete, since steel with a concrete filling only seldom proves sufficiently economical for this method of construction. It will be adopted when, in consequence of unfavourable building ground, the building materials are to be subjected to very great stressing, which cannot be ascertained in advance. In service the steel caissons show no drawbacks, as is proved by the large works carried out by German firms at home and abroad.

Finally, mention should be made of certain parts of the equipment of traffic structures in waterways, to which I have previously referred briefly. These are principally bollards, ladders, mooring bitts and rings, corner protectors, etc.

The chief requirement of the steel here is a very great resistance to abrasion. Since the quantity of steel coming into question is always small, the composition of the material may be chosen of much higher quality than is possible in the case of the great quantities of steel for the main parts of the structures.

With corner protectors, care must always be taken that it is possible to obtain really effective attachement to the masonry or concrete, since, in consequence of the shrinkage of the concrete and fairly great expansion, a space will be formed between the steel and the concrete.

5) Possibilities of development.

As will have already been seen from the production figures given in section 3. the use of steel in foundation work and hydraulic engineering has progressed with extraordinary rapidity during the last 15 years. This is doubtless to be attributed to the fact that the makers have been doing everything possible to improve the material and to develop the shapes of the structural members, in order to make them suitable resistant to the various stresses.

We must, however, clearly understand that in steel we do not possess a material which can eliminate all the drawbacks of wood and reinforced concrete. Steel is particularly subject to corrosion, and this still limits the possibility of adopting it.

It will be easier to get an increase in the moment of resistance of sheet piling and piles once the rolling mills have made considerably more progress towards producing larger sections, and welding technique has given us the possibility of adopting shapes which can suit requirements in any particular case.

The obtaining of a steel which will fulfil the stipulated requirements more efficiently is the case at the present day, can only become possible by close collaboration between physicists, chemists, steel makers, owners of rolling mills. mathematicians, designers and builders, whereby the experience gained with works already executed will play a very important part.

Summary.

The paper gives a compilation of experiences gathered with the application of steel for underground and hydraulic structures. The physical and chemical behaviour of steel is explained, if subjected to the influences of air, water, and alternating changes between water and air. The means of keeping these deleterious effects as small as possible are mentioned, as well as the life time of steel structures. The counteracting measures to reduce destruction are: the composition of steels, painting, metal covers, encasing in concrete, and the shape of structural parts. A short description of the development of steel production for the use in hydraulic structures is given, in particular steel sheet piling. The claims put in steel sheet piling are discussed. Steel can also be used for piles, wells, caissons, and equipment such as bollards, ladders etc.

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