論説報告

土木學會誌 第十六卷第一號 昭和五年一月

PREVENTION OF DAMAGES TO ENGINEERING STRUCTURES CAUSED BY GREAT EARTHQUAKES

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Synopsis

The object of this paper is to describe briefly the outstanding features of the damages done to various engineering structures by the great earthquake of Sept. 1, 1923, and from the costly lessons drawn from them to suggest such modifications of the usual methods for the design and construction as are most likely to minimize the damages on the recurrence of similar catastrophe.

The treatment of the subject is entirely from the practical point of view; as to theoretical disquisitions they are to be sought in the publications of the special committee as well as in those of the Permanent Earthquake Investigation Committee.

Introduction

While the effects of seismic action on structures have been a subject of numerous dissertations, it is a matter of rare occurrence in the lifetime of an individual to be an eye-witness of destructive actions wrought by a great earthquake — 68 years intervened between the last two great ones — even in a country like Japan, visited so often by earthquakes.

The great earthquake with which we are now concerned had its origin at the sea bottom about 100 km, SSW of Tokyo, and caused destructive actions over some 5 000 sq. km. The greatest accelerations as observed were 3 500 mm. per sec. per sec. at Yokohama and 800 mm. at Tokyo. The effects of this earthquake on engineering structures have been more closely studied than any of the preceeding ones, throwing considerable amount of light on their nature, thanks to the laborious work of the scientific societies in Japan.

Doboku-Gakkwai (civil engineering society) instituted a special committee, consisting of nearly 100 members, shortly after the catastrophe, and after full three years of investigation succeeded in collecting valuable data which have been printed in 3 large volumes. It is from these reports as basis that the present paper has been prepared.

The structures taken into consideration cover almost the whole field of civil engineering practice, being divided as follows:

(1) Water supply
(2) Sewerage
(3) Gas works
(4) Railways
(5) Maritime works
(6) Hydro-electric works
(7) Roads and Bridges
(8) Buildings

(1) WATER SUPPLY

The water works located within the strongly shaken district were those of Tokyo, Shibuya, Tamagawa, Kawasaki, Yokohama, and Hadano. None of these works escaped damages as were not great enough to throw the whole works out of operation. In this, only the damages to Tokyo Water Works, by far the largest of all, will be considered.

The original Tokyo Water Supply dates 270 years, the water having been drawn from the Tama River by an open canal 5 to 10 m. in width and 1 to 3 m. in depth and more than 40 km. in length, mostly excavated in firm natural ground.

In modernizing the water supply in 1892–98, the old canal line was partly utilized as far as the pumping station which is located in the outskirt of the city. The new works were designed to supply 220 000 cu. m. per day. The extension works to double this capacity were in course of execution at the time of the catastrophe.

The damages to *the canal* were not serious, but necessitated the closing of the intake gate and keeping it shut for 12 days. This was caused by the failure of embankments which at places carried the canal. They have shown (1) that no artificial mound of earth can be fully relied upon as that formed by nature, (2) that embankments are to be avoided as much as possible, as they are generally constructed on low grounds which lack in firmness, and are moreover subject to overflows necessitating drains and culverts which add to the weakness of overlying banks, (3) that the use of earthenware pipes, and bricks, which were the only materials available, at the time of construction for drains and culverts are not fitted to resist earthquake shocks, (4) that the surging of running water sideways cause the washing of the banks, especially when cracks had already appeared in the embankments, (5) that it is advisable to use metallic pipes in place of open channels, notwithstanding the larger cost. In the repair and reconstruction work, the open canals have been either lined or wholly built with reinforced concrete, and the banks secured against surging by building parapet walls alongside. The brick culverts have likewise been replaced by reinforced concrete ones. A new feature in the repaired canal work is the connection made between the old and new canals, provided with an electric pump, thus doubling the watercourse to meet any future emergencies.

The Settling basin, *Filter basins* and *Clear water basins* were more or less damaged, but none seriously. The settling basin which had its sides pitched to a slope of 1 in 1.5 with stones laid on clay puddling sustained almost no damages and continued to supply the water found in them. The filter and clear water basins whose sidewalls were of concrete or of brick work, and the bottom of plain concrete were fractured at places, differing in extent according to the nature of the ground in which they have been built.

The Pump House including engine room, boiler house and chimneys being entirely of bricks (built in 1897) suffered considerable damages. They have since been rebuilt with reinforced concrete. Of the 6 pumps 3 had their delivery pipes (500 mm. in diam.) ruptured at the flanges. The force mains consisting of high and low services, each served by two 1 100 mm. pipes sustained large cracks, putting all the pumps out of operation. Outside the house, two brick chimneys 37 m. in height had their upper 3 m. broken off. The repair to the pumps was immediately taken up, putting them in operation in less than two weeks.

The damages to *the distributing system* were not so great as at first imagined. Of the 982 000 m. of cast iron pipes of all sizes the number of injuries sustained, excepting those in the greater part of the burnt district were as follows:

Pipes ruptured	227
Hydrants injured	112

Cut-off valves broken	31
Meters and Check valves put out of order	12
Total	382

The smaller pipes were the most injured; the damages to submains of more than 400 mm. were only 16 in number. The most injured pipes were those laid in soft ground. Out of about 330 000 lead joints, 260 000 showed leakages in varying degrees, leaving only 70 000 intact. The greatest impairment to the distributing system was caused by the destruction of the bridges, (of which there were 110) carrying the pipes, by fire, and the melting of joints and lead pipes in the burnt section of the town, the latter numbering 155 000 cocks, all of which loss were borne by the respective owners. The reparature as well as all expedients were carried out as speedily as possible, so that the city was again supplied with water in about two weeks after the disaster. The important points to be observed in laying pipes have been found to be (1) to choose the best ground possible, (2) to lay them as deep as possible, (3) to avoid rough handling of the pipes in laying, (4) to avoid all constraints at the joints, (5) to see that individual pipes are of uniform thickness, (6) to avoid using bridges for carrying pipes across canals and creeks, prefering syphons, (7) to reinforce the pipes in some way when passing s ft grounds, (8) to duplicate the system of supply, wherever possible, by connecting the mains at suitable points.

Extension Works The first extension works of the Tokyo Water Supply which were nearly completed at the time of the catastrophe furnish several important points for study. The new works were for supplying 3 million inhabitants with 170 litres per capita and diem, being nearly a double of the then existing supply. For this, the water is taken also from the Tama River, but by a new route 36 km. in length, interposed by an impounding reservoir 18 400 000 cu. m. in capacity. The reservoir consists of two portions, differing 13.6 m. in elevation. The partition dam which was finished in Jan. 1923 is of earth, 24 m. in height. The earth was rolled in layers of 15 cm. in thickness and compressed to 10 cm. The core wall is of clay & gravel mixed in proportion of 2 to 1. By the shocks the dam was lowered by 20 cm.

Other parts of the extension works sustained more or less damages, but none of particular significance. There were 204 pipe ruptures and 41 000 points of leakage. They were mostly in pipes under 30 mm. and in those laid in soft ground.

Summary To recapitulate the conclusions reached at in studying the damages to the Tokyo and other water works, they are as follows:

(1) For structures to be resistant to earthquake shocks, the first requisite is firm ground.

(2) For basins pitched side-slopes are to be prefered to vertical walls.

(3) Reinforced concrete is to be recommended for use in all subsurface construction.

(4) Every pipe should be of uniform thickness and of sound structure.

(5) Syphons to be prefered to bridges for crossings.

(6) The weakest points in a pipe-line are at the joints. Carefull investigations made by a special committee of the Engineering Society have led to the establishment of earthquake-proof joints, as fully described in the report of that committee.

(7) The use of wooden pipes which was a feature in Tamagawa water works, in which 40% of the distributing pipes were of wood, and joined with cast iron thimbles showed failures of 0.64 in 1 000 m. against 0.12 in 1 000 m. of cast iron ones in Tokyo.

(8) The use of earthenware pipes, as found in the Hadano water works gave the worst results, having had 1 in 3 pipes ruptured.

(9) For structures above ground surface steel proves to be the most reliable material.

(10) Earth dams can never be perfectly relied on.

(2) SEWERAGE

The only system of modern sewerage found in existence within the strongly shaken area, was in Tokyo. Even in the latter, the construction was still in progress (commenced in 1911) and only 20% of it was in operation. These sewers as constructed varied in size and form, the largest being of rectangular section 3.6 m. across and 2.4 m. high, built of reinforced concrete. The damages they sustained were not great, having been confined to cracks mostly found in the vicinities of manholes, branches and bends. The longitudinal cracks were comparatively rare; the most common ones were either cross or diagonal. All the cracks were found in sewers passing through soft grounds and almost none in firm ground districts.

The depth at which the sewers have been constructed played an important role. The greater part of the damages occured at a depth less than 3 m. from the ground surface. The damages to manholes were cracks appearing mostly within about 2.6 m. from the ground surface or at the junctions with the sewers.

The purification plant built at the outlet of the sewers sustained considerable damages, but not to the extent of being put wholly out of service for long, nor of any kind peculiar to the construction. An outstanding feature was the greater extent of injuries done to constructions on and in the made ground than to those in the natural one.

(3) GAS WORKS

Large gas plants that were found within the stricken districts were those of Tokyo and Yokohama. We shall be occupied with the damages to those in the former only.

The Tokyo gas works were put in operation in 1877. At the time of the catastrophe, there were 5 gas plants in the city, furnishing 640 000 cu. m. per day and distributed by mains and branch lines of 1 600 and 1 070 km. respectively in length, all of which sustained more or less damages. The supply was for a time entirely stopped; but the speed with which it was restored may be seen from the fact that of the 251 519 gas-meters then found installed 46% were again in operation 3 weeks after the disaster and the rest in less than 6 months.

Gas-holders The gas-holders which were 13 in number taken altogether were of 1 to 5 lifts, and varied in capacity from 1 400 to 100 000 cu. m. provided with tanks 14 to 60 m. in diam. and 5 to 10 m. in height. The immediate effect of the shocks on these holders was the disturbance of water contained in the tanks, which surged violently and fell like cataracts. The real damages to the structures were found to be comparatively slight. In smaller holders (under 30 000 cu. m. cap.) all the guide rollers were thrown out, causing the holders to cant, while in the larger ones only one or two rollers were dislocated. The total immunity from fire, even when they stood amid the conflagration of the surrounding buildings was something astounding.

Pipe Systems The main pipes varying from 75 to 1 200 mm. in diam. were nearly 1 600 km. in length, buried to a depth of 0.6 to 1.2 m. Breakages occurred mostly in pipes smaller than 200 mm. diam.; the smaller the pipes the greater being the number of ruptures. The total number of breakages were 110. The loosened joints were numberless, and have not been wholly located for some time. In this the smaller pipes were again the greatest sufferers.

In the elevated parts of the city, where the grounds are of compact loam, hardly any damage was incurred, while in the lower districts with soft grounds, and especially in reclaimed land and old river beds the damages were considerable.

The precautions to be taken in laying gas-pipes were found to be similar to water pipes, being (1) in providing the pipes with foundation by driving piles, when laying in bad grounds, (2) in avoiding laying main pipes close to moats and canals, (3) in laying in as great a depth as possible; the minimum depth being not less than 0.9 m. for small pipes and 1.2 m. for the mains, (4) in providing the mains with automatic cut-offs, (5) in devising joints better than the present ones of lead.

The gas plants of Yokohama sustained greater damages in some respects than those of Tokyo, owing to its greater proximity to the seismic centre; but the general features of the damages were alike, so that the precautionary measures stated above receive only the greater emphasis.

(4) RAILWAYS

Of the government railways traversing the roughly shaken regions, the lines in operation were nearly 1 130 km. and the total track length, 1 750 km. The damages to some of the lines were tremendous.

Earthworks The sliding of side slopes in cuttings were almost innumerable, aggregating in volume to no less than 370 000 cu. m. All the embankments were more or less shaken down, leaving in extreme cases the tracks hanging in the air. No less than 77 km. of embankments settled to an extent of making the trains incapable of running. There were more than 28 000 sq. m. of retaining walls in cuttings, and 22 000 sq. m. along the embankments that were overthrown. Low walls built along the platforms were damaged to an extent of 4 000 m., of which about 180 m. were completely overturned.

Bridges The failures of bridges were mostly in the substructures, the metallic superstructures remaining almost entirely free from injuries except from bodily fall. Of the 2 056 masonry abutments then in existence 337 were seriously damaged, and of 945 piers 279 were either dislocated or overturned. Out of 293 arch and box culverts 9 were found damaged.

Tunnels Of the 116 tunnels totalling 40 000 m. in length 82 received damages. The injured portions were 2 400 m. in length. The greater part of the injuries were in the vicinity of the portals, caused by the sliding of the sloping ground above. The cracks in the tunnels proper took place where either soft earth, or faults in rock were met, but against which the linings had not been made thick enough.

Buildings The buildings destroyed were 409 000 sq. m. of built areas, of which 169 000 sq. m. were due to the shocks; the rest were by fire. Wooden buildings were comparatively free from earthquake damages. Stone and brick houses naturally suffered most, having had 430 sq. m. of them completely demolished and 26 400 sq. m. seriously damaged. Reinforced concrete buildings were also considerably injured; but those completely destroyed were few. The only large steel-frame building was the Tokyo Central Station, which withstood the shocks without sustaining any injuries to speak of.

Tracks Out of the 1 750 km. of tracks, 286 km. were deranged. Some of the notable damages done to the tracks were on embankments, throwing the track in one case to a distance of as much as 26 m. In deep cuts the tracks were buried deep under the earth slides.

Trains At the moment of the catastrophe there were 112 trains running in the strongly shaken zones, and of these 23 were either simply derailed or completely overturned.

Miscellaneous The damages to crossings, signals, watersupply, cables, etc. were out of number.

Local Urban, Suburban Railways These were by no means free from damages; but the absence of large structures kept the extent of injuries far within the bound of those in the main lines. It is remarkable that the elevated railway in Tokyo, having continuous spans of brick arches, sustained hardly any damages.

Conclusions Various as are the kinds of railway structures and the nature of the grounds on which they have been built, the damages incurred were still more diverse, so much so that no definite conclusions have been reached at, in spite of labourious investigations. However, the following may be of some importance in designing and carrying out the various works common to most railways.

With regard to *earthwork*, the side slopes of cuttings are most likely to be shaken down: (1) where stratification slopes toward the roadbed, (2) when hard strata overlie soft ground, (3) when the ground lacks uniformity in nature. *Embankments* are most liable to be demolished: (1) when built on soft ground (2) when the height is considerable, (3) where they are behind bridge abutments, (4) when made up of decidedly sandy soil; gravel proves to be much better than sand in this respect. Sodding the slopes both in cuttings and embankments adds to their strength. Footwalls increase the stability of the slopes, especially in case of embankments. While there is no doubt that the flatter the side slopes, the more resistant will be the cuttings or embankments, the critical slope has not yet been determined.

With *bridges*, the modes of failure of abutments were various; and stated in the order of the number of occurrence they were: (1) inclining forward, (2) sheared horizontally, mostly near to the ground surface (3) shearing of track-parapets, (4) overturning completely, (5) sinking where the ground was soft. The injuries to wing walls were more numerous than those to abutments. Piers sustained no less damages than abutments; they were mostly: (1) by being sheared horizontally close to the ground surface, generally at the junction to the foundation, (2) dislocated more or less, (3) sheared and overturned, (4) inclined and sunk where the ground was decidedly soft.

Firm foundation is of paramount importance for all masonry work, irrespective of the nature of the ground. Even in the lower districts of Tokyo, where soft ground prevailed, the elevated line structures which had good foundations stood remarkably well. In all works mass concrete proved to be better than brickwork, so did reinforced concrete than plain concrete.

As to bridge superstructures, with the exception of those that fell owing to the failures of the substructures, the only damages done were the bending or tearing of anchor bolts in some cases.

In *tunnels*, as most of the damages sustained were, as already stated, in the proximity to the ends, where the earth coverings were moderate, notwithstanding the considerable strength generally given to the arch rings toward the extremities, it is evident that still greater thickness is necessary than is usually provided for them.

For all future constructions on railways, unless iron or steel is to be solely used, reinforced concrete will be the material to be recommended; but the care with which the work is carried out is of no less importance than the choice of materials.

(5) MARITIME WORKS

Harbour Works

Yokohama and Yokosuka were the only harbours lying within the strongly shaken area, that were provided with breakwaters and equipped on modern lines. The former, the chief commercial port of the country, was furnished with docks and various kinds of terminal facilities; while the latter being a naval port was fully equipped as such. The present discussions will be confined to the damages to the Yokohama harbour works only.

Breakwaters Of the length totalling 3 683 m. the portions built on silty bottom (about 1 330 m.) were severely damaged, having been sunk about 2.3 m. on an average, and getting at the same time inclined toward the sea and giving rise to some irregularities in the alignment. The breakwaters were built of concrete blocks regularly set on rubble mound, and crowned with concrete in situ.

The pier heads which were 13 m. in diameter, and more solidly built than any other parts were sunk 3.3 m. It is a remarkable fact that this sinking was simply vertical, so that the lighthouses which stood on them continued to be serviceable after the disaster.

From the foregoing it is to be learned that to make a structure of this kind secure against earthquake shocks nothing is better than to build a monolithic wall on firm bottom, and where the overlying material is soft to dredge the bottom and replace it with rubble. Further, if blocks are to be used for the superstructure, to bond them firmly with joggles, and cap them with massive concrete of sufficient thickness.

Quay Walls The quay walls which were 2 000 m. in total length had hardly any part of them that escaped injuries; only a little over 400 m. retained its position. The quay walls were built, with an exception of about 170 m., entirely on layers of massive shale cut in steps and levelled with concrete in situ and in bags. The walls consisted mostly of 5 courses of concrete blocks 10 to 14 tonnes each, laid without connections of any sort whatever, and built to a front batter of 1 in 20, and crowned with massive concrete 3.2 m. in height, making the total height 10 to 12 m. with a bottom width of 4.5 to 5.5 m. They were built in sections of 11 m. in length, each section being made independent of one another. The backing was of rubble and the backfilling almost entirely of the fragments of shale.

By the earthquake shocks, the blocks were either slid or overturned. It is remarkable that while the overturned walls were those founded on solid shale, a small portion built on rubble mound filling the deep gullies was found to have been merely slid. The outward motion of the walls was evidently due to the pressure of the backfills, added to the accelerating force of the earthquake. While the latter is uncontrollable, the former may be decreased by the use of stone cribs or other kinds of self-retaining construction.

It will be seen from the preceeding, that apart from the nature of the ground, strong union of the component parts is the first requisite in increasing the stability of a quay wall against shocks. Either monolithic construction or adequate joggling of the blocks might prevent the damages to a great extent.

In the reconstruction work, the greater part of quay walls has been transformed into open construction by using steel plate girders resting on solitary piers of large caisson blocks, which is considered as improvements so far as its resistance to earthquake is concerned.

Landing Pier The metallic pier 500 m. in length became a total wreck. The weakest part of it was the original structure with cast iron piles 30 cm. in diameter, 13 cm. in thickness, and about 15 m. in length, set 4.6 m. apart, which were all broken at the flange joints. It was provided with wooden floor 19 m. in width, laid on I beams. In 1916 it was extended to 42 m., using reinforced concrete for the addition, and for the substructure 2 solid steel piles 16.5 cm. in diameter and about 22 m. in length, interposed with 2 reinforced concrete piles of Mouchel type 1.37 m. in diam., every 3 rows, all braced with metallic rods.

While the solid metallic piles were not materially disturbed, the reinforced concrete ones were sunk 15 to 22 cm. and in consequence distorting the floor considerably, which however remained serviceable for quayage.

These facts show most clearly the inadaptability of cast iron piles for such construction, no matter how small the amount of incumbent load may be. It will further be seen that the depth to which the piles are sunk is a matter of no small moment in stabilizing the structure and is not to be determined by the vertical loading alone.

Sea Walls Sea walls as built in this country in a sheltered water front are most usually of rough stone pitching backed with rubble and rarely with concrete. The foundations are equally simple, consisting of a sort of grillage which in soft ground are made to rest on short piles, or on a layer of rubble at best. In Yokohama nearly all the canal walls with a total length of 40 000 m. were almost entirely overturned or bulged out. In Tokyo more than the half of all the walls of this kind were more or less damaged.

Judging from the portions which withstood the shocks comparatively well, stone pitching backed with concrete and rubble, with bodily connection with the foundation is a decided improvement. The reduction of back-pressure by good choice of back-filling material, and the driving of piles to firm ground are essential for sound construction.

Wooden bulkheads which were used for temporarily retaining the earth filling were destroyed, where the piles were not driven to a sufficient depth.

Walls built of two or three courses of concrete blocks, each weighing 4 tonnes, laid on rubble mound and surmounted with cemented rubble, and used as quays for smaller crafts, both in Yokohama and Tokyo, were mostly overturned, owing to the sliding of the blocks. Had the blocks been sufficiently joggled, the walls might have resisted the shocks.

Graving Docks There were 3 old and 2 new graving docks in Yokohama, and 5 more within the severely shaken area. All these docks with the exception of the one in Tokyo were cut in soft rocks and lined with concrete. They were all free from serious damages, except one in Yokohama, in which one side-wall gave in and several cracks appeared in the other parts.

As to whether the docks were flooded, or kept dry seem to have made no difference in their behavior to the shocks.

Lighthouses

There were 10 lighthouses within the area circumscribed by a radius of 100 km. from the seismic centre. Those most damaged had towers of plain concrete, brick or stone. The following cases are representative of them :

Oshima Lighthouse which stood not far from the seismic centre was 10.6 m. in height, built of plain concrete. It was sheared at the height of 4 m. and slid about 30 cm. rotating 15° anticlockwise, but not overturned.

Jyōgashima Lighthouse, 40 km. from the seismic centre, was a brick structure 5.8 m. in height. It was totally wrecked and swept away by the tidal wave.

Tsurugigasaki Lighthouse, equally distant as the preceeding one from the centre, was one built of stone and was 7.6 m. in height, with walls 1.3 m. in thickness. It was completely demolished under the shocks; the acceleration was in each case estimated at 4 000 mm. per sec. per sec.

Sunozaki Lighthouse, also distant 40 km. is a reinforced concrete structure, 12.2 m. in height. It was bodily raised 1.5 m. with the ground, but was not otherwise damaged.

Haneda Light Beacon, 82 km. from the seismic centre was a light structure resting on cast-iron screw piles. The breakage of the piles led to the total loss of the structure.

The optical apparatus were immune from injuries, at least those that remained to be seen. There was a case of the mercury surged out of its basin.

The following points have been noted in the damage to lighthouses:

(1) Building close to the edge of precipice is to be avoided.

(2) Accessory buildings are either to be entirely separated from the lighthouse, or connected, if necessary, by light corridors.

(3) Reinforced concrete is the most appropriate material to be used for the construction of towers.

(4) Concrete foundation is to be made extra wide and massive.

(5) The use of cast-iron piles is to be avoided.

(6) HYDRO-ELECTRIC WORKS

Hydro-electric development works, of which there were 91 within the strongly shaken area, sustained more or less damages in all their parts, except the machineries which were almost all free from any serious injuries.

Intake Dams Intake dams are generally not only moderate in height, but are built on rocks, so that they were mostly free from great damages. In a few cases, piers on the crests of overflow dams were sheared off, but the main body remained intact. There was a dam with the top width of 1.2 m., 11 m. in height and 35 m. in length that sustained 2 large fissures 3.5 m. deep produced in it.

Dams of this class should have extra width given them, and be built with gentle slopes on both sides, avoiding the steppimg of the sides. Slender piers for the flood openings are conductive to serious damages.

Power Canals The damages to power canals were greatest in open ones, especially when they were built along hill sides, where the breaks produced in the embankments allowed the water in the canal to run down the slope, carrying with it the whole earthwork. The land slides taking place above the canal caused the most serious damages to the latter by filling it up and making it slide down the slope. Wooden as well as reinforced concrete conduits were at several places carried down by the land slides.

Tunnels were comparatively free from damages, especially where the overlying materials were thick; but those built in soft ground were all seriously damaged. Generally smaller tunnels sustained much less injuries than larger ones.

As a precautionary measure, the location of open canals on hill sides is, in the first place, to be avoided as much as possible. In open canals, the side slopes are to be made gentler than in other kinds of work, using, at the same time, large radius for the curve connecting the side and the base. Conduits passing along hillsides should be laid underground. (See also under Water works.)

For a tunnel in soft ground the lining should be fully strengthed with metallic armatures. All tunnels are to be reinforced near to their extremities and all possible precautions taken against earth slides.

Headbays Of 15 headbays which were more or less injured, 5 were almost totally wrecked. The latter were those built in soft grounds.

Headbays are generally built in the proximities of salient points of elevated ground, making them most liable to attack by earthquake shocks. As their sidewalls are high (those of the damaged ones were 6 to 10 m.) the lateral forces to which they are subjected must be very great.

Therefore beside building them on firm ground, wherever possible, they should be provided with partition walls properly reinforced to make them sufficiently resistant to earthquakes.

Penstocks The damages to penstocks were mostly due to landslides as well as to the overturning of anchorage blocks; the failures of pipes in themselves were comparatively rare. The latter were in loosened rivets and packings which were readily repaired.

Massive anchorage blocks founded on firm ground are essential to the safety of penstocks against severe shocks.

Transmission Lines The fall of towers and poles were mostly due to landslides; those directly caused by the shocks on level ground were rare. The rupture of wires and cables were caused more by the failure of their supports than by the vibrations to which they were set by the shocks. Of over 7 000 towers, only 50 actually fell down, while 300 got either tilted or bent.

These damages clearly show that it is always advisable to locate transmission lines on the crests of elevated lands, avoiding the slopes and low lying lands as much as possible.

(7) ROADS AND BRIDGES

Roads At the time of the great earthquake the greater part of the more important roads in the country were in the course of reconstruction. In Tokyo, where about one-eighth of the city area is taken up by streets, whose paved roadways and trottoirs were then but 4% of the whole, the injured portions amounted to little over 15% of pavements of all sorts taken together, and the latter mostly by fire.

In Yokohama, where the roads occupied 1/12 of the city area, they had 54% of the whole damaged.

The roads lying outside of the cities were mostly of earth and gravel, except the national road between Tokyo and Yokohama, which were then in course of being paved. The part lying in the Tokyo Prefecture was mostly on low embankments, nowhere exceeding a metre in height; they were compacted with heavy steam rollers. The roadway was of asphalt 6 cm. in thickness, laid on 15 cm. concrete, with trottoir on each side, the latter having concrete slabs laid on sand. The effects of the shocks were in causing settlement of the roadbed at places, where the ground was soft and in cracking the asphalt at numberless points. The other half nearer to Yokohama, which had asphalt laid on old macadamized road, was almost entirely free from cracks. These facts appear to show that for asphalt pavement bed of macadam is much superior to that of concrete. In soft ground, there is hardly any doubt that reinforced concrete bed is a necessity.

Inside the city limits of Tokyo, the damages to roads due to the shocks were most marked in soft and especially newly made ground, irrespective of the natural formation of the land.

In Yokohama, the lower part of the town, where newly reclaimed land predominates, the settlement of the ground was considerable, amounting to 1 to 2 m. at places along the canals, leaving the bridges clear above the road surface.

Elsewhere, the subsidence of high embankments took place at numerous places; in some cases the amount attaining as much as 20% of the original height. The failures of retaining walls were equally great in number and extent.

Regarding the comparative resistance of different kinds of pavement to the shocks, nothing conclusive has been arrived at, owing to the existence of a comparatively small amount of paved roads at the time of the catastrophe. However, there was no doubt that brick pavement was the one most liable to injury by the shocks.

Most damage to pavements were due to the fire, and in these no kind was exempt, whether they were cf stone, asphalt, or impregnated blocks; only the brick was comparatively immune.

Trees planted on sidewalks were found everywhere to be an efficient protection against the spread of fire.

Trottoirs in front of large buildings were thrown up, caused by the motion of the latter, showing that such pavements should be laid clear of the buildings.

It was seen that the direction of earthquake shock has much to do with the extent of damages inflicted, in that the latter were generally greater where the two were more nearly at right angle.

Another point to be noted is the elevation of the ground. The highest part of Tokyo is about 39 m. and the lowest 50 cm. above the mean sea level. For the same nature of the ground, the roads in the higher district sustained more damages than those in the lower, most likely owing to the greater number of precipitous cuttings in the higher part of the city.

Bridges In Tokyo there were 669 bridges at the time of the disaster. Of these, 70 sustained damages from the shocks, and 289 got destroyed by the fire; the latter had been of wooden construction or of metal with wooden flooring. Stone bridges subjected to fire had all their exposed surfaces spalled, while the all-metallic as well as reinforced concrete ones were generally free from damages. The visible effects of the shocks on bridges were mostly confined to abutment-walls, posts, piers and ornamental parts, and excepting but one case, they were not so great as to make the bridges impassable.

In Yokohama where the shocks and fire played havoc with bridges, 11 of them were overthrown, and 37 consumed by the fire, leaving hardly any unscathed. The fire started not only from the blazing houses, but also from the burning crafts which were found tied near the bridges.

Outside ef urban districts the damages to bridges were no less than within, the greater number of cases were being due to the failure of the substructures and wingwalls which had apparently been designed without any consideration of earthquake shocks.

As far as the superstructures are concerned, it may be stated that steel and reinforced concrete make the safest bridges against fire and shocks. As to the type of construction, there is but little to choose, simple girder being without doubt the safest type, while continuous girder, arch and suspension are likely to be affected by any motion of the substructures. (For railway bridges see under Railways.)

(8) BUILDINGS

Houses The most appalling damages within the city of Tokyo were those to dwellings and business buildings. Of 326 230 houses within the city 35 800 were more or less seriously damaged, and by far the greater part of them by the fire. The damages solely due to the earthquake were those to 5 796 houses (outside of the burnt district) divided as follows:

	Collapsed	
	Partially.	Totally.
Wooden frame	3 970	1 487
Stone or brick with wooden frame	25	7
Stone	43	18
Brick	173	51
Steel frame	3	4
Reinforced concrete	0	6

Wooden frame buildings such as those collapsed under the shocks had all the weakness inherent to the old types of construction viz: heavy roofing, weak joints, slender columns and frail external walls. These houses were rarely more than two stories high.

The godowns which are generally fireproof are but little resistant to earthquakes. Their heavy earthen walls, held in place with bamboo lath, get easily separated and fall down under strong shocks. In the burnt districts where there were 440 godowns, 120 remained intact. Walls of stone or brick nailed to wooden frame met the same fate as those of earth. The connections between the walls and the frame should be made much stronger than are ordinarily the case, to be resistant to great earthquake shocks.

The use of expanded metal and concrete for walls of say 4 cm. in thickness, strongly connected to the wooden frames was found to be quite resistant to shocks as well as fire.

Tiles used for roofing in the customary manner, i. e. simply laid on a layer of earth spread on shingle were everywhere slid down the roof in a desultory manner and aided the spread of fire.

There is no question that wooden frame building when strongly braced, and provided with light roofing and strong walls, and with sills rigidly connected to the foundations will defy the attacks of such earthquakes as have hitherto occured in Japan.

Ordinary *stone and brick* houses, 2 to 3 stories high, were wrecked more than any other kinds, considering the number in existence. This fact was most marked in Yokohama, where almost all the old brick houses were totally demolished. In the Tokyo Prefecture 5 946 out of 6 969 brick houses were more or less severely damaged ; those in which lime mortar had been largely used in joints were completely wrecked. Modern construction in which cement mortar was liberally used and cares in laying exercised suffered much less serious damages. The walls were naturally the weakest portions; they were the first to fail, leading to the collapse of the whole. The roofs and floors in themselves were generally unaffected; so were the foundations except those in soft ground. The damages to dwellings, in which were found a greater number of partition walls and columns, were found to be less than in factories and workshops with surrounding walls only. Generally the weakest parts of the buildings were at the corners and wings.

Steel frame buildings in Tokyo have mostly been of curtain-wall type, having walls of 1½ to 2 bricks, and sustained comparatively little injuries. There were, exceptionally, some of reinforced-concrete type; they were still more exempt from damages. The maximum height of these buildings are 30 m. being the limit fixed by the government ordinance.

Shortly before the great earthquake a somewhat novel system of construction was introduced, exemplified by Marunouchi Building, by American builders, having the rapidity of execution and lightness as its objects and was followed by native constructors to some extent. Most buildings of the kind sustained considerable damages, the thin walls and hollow blocks used, not being able to resist the stresses to which they were subjected.

Of 74 steel frame buildings in the Tokyo Prefecture 50 were almost uninjured, while the rest received more or less serious cracks in walls and in one case totally wrecked. They have shown that steel frame building thoroughly braced and built of reinforced concrete with strong connections carried throughout will make a really sound structure.

Next to steel frame in point of safety against shocks, comes *reinforced concrete building*. Of 598 buildings of the kind 9 collapsed, while 126 were more or less damaged. One of the principal causes of the damages was the weakness of the concrete used in the construction. The specified ultimate compressive strength of 175 kg. per sq. cm. and with it the allowable stress of 35 kg. did not seem to have been attained, owing to careless manipulation, and negligence in observing the important rules of fabrication. Further, the faulty disposition of reinforcements contributed to their weakness, cases of which were so numerous that even cursory inspections did not fail to reveal.

The damages to houses were extensive and so diverse in character that an attempt to make general statements is not only difficult but also would be of little value. Each structure must be studied by itself as to its weak points which were the cause of its damages. The reports of the Committee furnish the important details of injuries, as shown in over 500 photograghs attached thereto, for such studies. As to making the complete design of a building capable of withstanding great earthquake shocks, it is next to impossibility, since so many factors enter into consideration, of which the acting forces and the natural oscilation period of the building itself are almost unknown quantities to start with. The behaviours of existing buildings under the shocks have shown that the rigidity is the first requisite of construction, so that everything that contributes to it is to be embodied in the design. Whether this is applicable to all taller buildings is still a question that can only be solved by experience. That the unification of vibration periods in all parts of a building is to be aimed at is certain in all cases. Concerning the materials and details of construction there remains but little to be stated beside what have been touched on in the preceeding.

Chimneys Chimneys are favorite objects for destruction by earthquakes. Of over 240 chimneys taller than 15 m. found in Tokyo and Yokohama at the time of the catastrophe more than 110 were totally wrecked, and over 40 seriously damaged. It is remarkable that the point at which the rupture took place was almost anywhere in the whole height, contrary to an old idea that it should be at 2/3 the height in tall chimneys.

Brick chimneys naturally formed the greater part of the damaged ones, owing to their weakness at the joints, which according to actual tests were found to be 1.5 to 3.5 kg. per sq. cm. in tension, whereas the stress caused in them by the shocks should have exceeded 7 kg. per sq. cm. in many cases. Brick chimneys reinforced on the outside, lengthwise as well as crosswise, sustained far less damages than plain ones.

Next to brick chimneys in order of the extent of damages were the reinforced concrete ones. The causes of the damages in these were insufficient reinforcements and weakness at work joints, aggravated by the want of care exercised in construction.

The metallic chimneys naturally withstood the shocks better than any other kind. Those that were wrecked were mostly due to insufficient anchorages. The guys frequently used for those of smaller diameters were not found to be as effective against earthquake shocks as might have been expected, owing to the lack of concerted action of the stays.

The determination of the dimensions of a chimney sufficient to resist the actions of great earthquakes is not simple; but when proportioned by supposing the acceleration at the lower end to be equal to that of the ground (say 3 000 mm.), and assuming it to increase by 50% near to the top, it would be strong enough in most cases.

General Conclusion

The foregoing are the outstanding features of the damages wrougt on common engineering structures by the great earthquake of Sept. 1, 1923 and some of the practical lessons drawn therefrom.

From what has been stated it is to be seen that it is hardly possible to make all engineering structures entirely safe against the actions of destructive earthquakes, the difficulties arising more out of economic ground than of technics. Much, however, could be done toward the avoidance of serious damages by keeping in view the essential points stated in the preceeding.

Closer studies of the damages will bring out many more useful facts; but they are beyond the scope of the present paper, and all further disquisitions on the subject are left to specialists in respective lines for whom the volumes of comprehensive reports of the Committee have been made available.

The End.