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STATE OF THE ART DEVELOPMENTS IN ICE SHELL CONSTRUCTION

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ABSTRACT: Snow and frigid conditions enable thin ice shells to be used successfully in cold and snowy regions. Structures designed using modern shell theory can cover areas larger than the classic snow-ice structures such as the Japanese *”kamakura”* or the igloo.

This paper consisting of: 1) structural engineering of ice shell construction; 2) the application to winter architecture in Hokkaido; 3) field experiments of big ice domes spanning 20-30 metres; and 4) an investigation of ice dome construction on frozen lake, demonstrates that ice shells can be used as architectural structures in cold and snowy regions for creating winter built environments.

1. INTRODUCTION

With the goal of constructing ice shells with spans from 20 m to 30 m, which could be used for a variety of winter structures in snowy and cold region, the author proposed a rational construction method based on structural and constructional engineering considerations at the beginning of 1980s (Kokawa 1985). Theoretical and experimental studies to determine structural safety and the construction technique were carried out (Kokawa and Hirasawa 1982/1983; Kokawa 1983; Hirasawa and Kokawa 1984; Kokawa 1984; Kokawa 1985; Kokawa and Murakami 1986; Kokawa 1988). 10 m span small ice domes were constructed for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese “sake” and a working space at the basement-area for Japan Observatory in the South-Pole (Kokawa and Watanabe 1997).

The results of these studies provided the opportunity to construct ice shells for an architectural space in Tomamu, Hokkaido. Many ice shells were used as leisure-recreational spaces for visitors about 3 months in each winter and these have created fantastic, beautiful spaces and unique built environments in winter (Kokawa et al. 2000). Taking safety into consideration, the size of these shells had been limited to not more than a 15 m span. However, the results of the past studies showed that a large ice shell with a span between 20 and 30 m would also be possible. Field studies on a 20-30 m spanning ice dome were carried out on the same site at Tomamu in 1999 to 2001 (Kokawa et al. 2001; Kokawa 2002a). These test-domes showed a high structural efficiency. Based on the results of these studies, it was concluded that a 20-30 m span ice dome would be practicable (Kokawa 2002b).

Recently, the author has been investigating the construction of an ice dome on a frozen lake. A numerical simulation for a 20 m span ice dome showed that a 100 cm thickness ice plate could support a 100 tf ring load for 2 -3 months (Kokawa 2004b).

2. STRUCTURAL ENGINEERING OF ICE SHELL CONSTRUCTION

2.1. Construction Method

The *"Kamakura"* and igloo are classic snow-ice structures, but it seems that these structures have neither construction rationality nor structural efficiency in the case of a large span. A *"Kamakura"* is a Japanese traditional snow hut where children play house during the New Year holidays, and is formed by scooping out snow from a small mound of snow. An "Igloo" is a snow hut built by arranging snow blocks hemispherically. These structures are applied to very small dome construction.

The following attempts for snow-ice dome construction were based on Neff's method of concrete shell construction (Ishii, 1977). Snow domes with a 10 m base diameter, was constructed by blowing milled snow over an inflatable hemisphere by a Peter miller (Mellor, 1968). Stanley and Glockner (1975) proposed a construction method of ice dome and carried out an experimental creep study on reinforced ice domes with a 2 m span produced by spraying water onto an inflatable membrane. The same method was also used for ice structures in Europe (IL9, 1976; Isler, 1979). However, these studies did not develop further because the technical devices such as the inflatable membranes of formwork were not suitable.

Since 1990s, a snow vault has been used in the northern parts of Scandinavian countries (Jordan et al. 2001; Makinen and Kilpelainen 2002). The snow vault is constructed by blowing snow on a high-rise arched mould and adding water or sea water directly into the snow shower while blowing (RIL 218-2002 2002). The inside span is limited to 5 m because the mould is heavy in order to support the weight of the accumulated snow during construction and the vault is subject to creep.

In contrast, large ice shells can be constructed by the following simple, quick and economical method so that they are both constructionally rational and structurally efficient (Kokawa 1985):

(1) build up a 3-dimensional formwork by inflating a 2-dimensional membrane bag covered with ropes anchored to the snow-ice foundation;

(2) cover the membrane with a thin snow-ice layer (1 cm) by blowing milled snow with a rotary snow blower, spraying water with a high-pressure adjustable nozzle and letting it freeze naturally at temperatures below -10°C;

(3) repeat the application of snow and water until the desired shell thickness is reached, then removing the bag and ropes for reuse.

The ice quality of the completed dome can be judged satisfactory if there is sufficient outward transmission of light from the lighted interior.

2.2. Feature of Pneumatic Form

One of the important features in this construction method is the air-inflated formwork. It consists of a membrane and covering ropes. The ropes play an important role in forming the shape of the inflated membrane. The tension in the ropes is in equilibrium with the inside air pressure. The membrane does not require 3-dimensional cutting because of the force control by the covering ropes. This makes membrane easy to fabricate even when the 3-dimensional form is complicated. Many different shapes could be made from the same membrane by changing the length and geometric pattern of the ropes. Because a uniform pressure decides automatically these forms, a compression membrane force works mainly in the completed ice shell, in spite of free-shape shell. So, this structure makes the best use of the snow-ice, which has relatively high compression strength. Furthermore, the general form obtained automatically by this method regularly consists of the same convex patterns. A family of reinforced ribs with large sectional areas along the ropes, would not only improve the structural efficiency, but also the geometrical beauty of the inside surface.

2.3. Snow Blowing and Water Spraying

In order to produce quickly a high quality of ice on the membrane, some special devices are needed. Snow is blown onto the membrane by a snow blower and tap water sprayed on the snow by a high-pressure adjustable nozzle. The snow is called "milled snow" which has a strong bond like a ceramic. The snow-water mixture formed on the membrane, is frozen hard some time later under the air temperature -10°C below. It is necessary during each blowing to keep the milled snow depth less than about 1 cm thickness. Otherwise, when water is sprayed, only the upper layer of the snow depth will change to ice and the membrane cannot maintenance the shape because of excessive weight. This causes material and geometrical imperfections as previously reported (Kokawa and Murakami 1986). The snow-water mixture solidifies more quickly than only water, and the ice seems to be more ductile. It normally takes 1.5 hours to attain 1 cm thickness. When the shell thickness reaches a certain value, it can support the weight of new snow-water layer. Therefore, the membrane does not need a high pressure and the formwork including the foundation is light and low cost. The application of snow and water are repeated up to the desired shell thickness, which is normally about 1/100th of the span.

2.4. Creep Behaviour

The strength of an ice shell is sufficient for some given loads over a short period. However, as the ice creeps, it is important to investigate the creep behavior of an ice shell, which will experience loads for a long time. So, experiments on ice domes under long-term loading (Kokawa 1983; Hirasawa and Kokawa 1984; Kokawa 1985) and the axisymmetric creep buckling analysis of ice domes (Kokawa 1984), were conducted together with at the beginning stage of investigations on the structural safety. Experimental creep tests (Kokawa 1985; Kokawa and Murakami 1986; Kokawa 1988), which were constructed based on the prescribed method. The important result of these tests confirmed that the ice shells slowly produce a large creep deformation before the collapse, if the quality of the ice remains good. It indicates also that the collapse does not occur abruptly, and that is enough time to predict the danger of the collapse. This ductile behavior makes use of ice shells possible for architectural structures.

3. APPLICATION TO WINTER ARCHITECTURE

Based on the fundamental studies since 1980 (Kokawa 1982/1983), and the ease of construction and high durability, the following experimental structures have been constructed. 10 m span small ice domes have been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese "sake", an exhibition hall for a winter festival and a working space in the basement-area for Japan Observatory in the South Pole (Kokawa and Watanabe 1997). In addition, many ice shells less than 15 m span, have been used since 1997 as leisure-recreational spaces for visitor about 3 months in each winter and these have created a fantastically beautiful space (Kokawa et al. 2000). Today in 2005, we have the following four places as shown in Table 1 to construct the ice shells for various kinds of winter activities.

Table 1. Meteorological data in construction place (http://www.data.kishou.go.jp/etrn/).

Construction Place (Usage)	Month	Air Temperature(°C)			Precipitation (mm)
		Average	Highest	Lowest	
Tomamu (Leisure)	1	-10.3	-4.0	-18.2	51.7
	2	-9.8	-3.2	-18.3	35.3
Asahikawa (Sake Factory)	1	-7.8	-4.0	-12.6	74.1
	2	-7.2	-2.7	-12.6	51.5
Syumarinai (Ice Fishing)	1	-9.6	-5.2	-15.5	150.0
	2	-9.5	-4.3	-16.4	99.5
Nakagawa (Workshop)	1	-8.3	-4.2	-13.8	89.5
	2	-8.4	-3.4	-14.8	52.9

Figure 1. Ice Shells in Tomamu (2002-2003 winter).

Figure 2. Ice Dome Concert (Tomamu).

Figure 3. Free-shape shell (Tomamu).

Figure 4. Drink-café (Tomamu).

Figure 6. Japanese 'sake' making (Asahikawa).

Figure 7. Workshop (Nakagawa).

4. FIELD EXPERIMENTS OF ICE DOMES SPANNING 20-30 METRES

4.1. Elastic Consideration

Theoretically, the use of an ice dome with a span of 20 m to 30 m is feasible. According to the membrane shell theory (Timoshenko and Krieger 1959), the compression stress at the apex of a spherical shell (with 30 m base diameter and 130 degree open angle) under dead type of loading (ice density 0.85 g/cm^3) is computed as 0.71 kg/cm^2, which corresponds to about 1/60th of the uniaxial compressive strength of ice. Therefore, the 30 m span ice dome has enough strength to stand, theoretically. This is the reasoning behind the field experiment of the 20-30 m span ice dome concerning the construction technique and the structural safety, which was subsequently conducted.

4.2. Field Test of 20 m Span Ice Dome

Two field studies on a 20 m span ice dome (17 m base diameter and 6.5 m height) were carried out at the site of Tomamu in 1999 and 2000. The following Figures and Pictures describe the construction and creep test of the year 2000's test-dome, and concludes that a 20 m span ice dome, as an architectural structure during winter in Hokkaido, is feasible (Kokawa et al. 2001).

Figure 8. Air-inflated membrane as formwork.

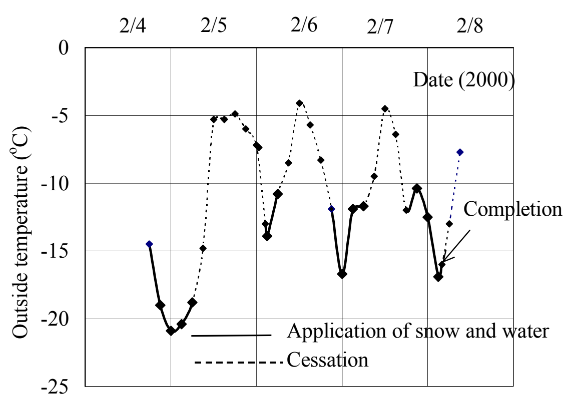

Figure 9. Outside air temperature during construction.

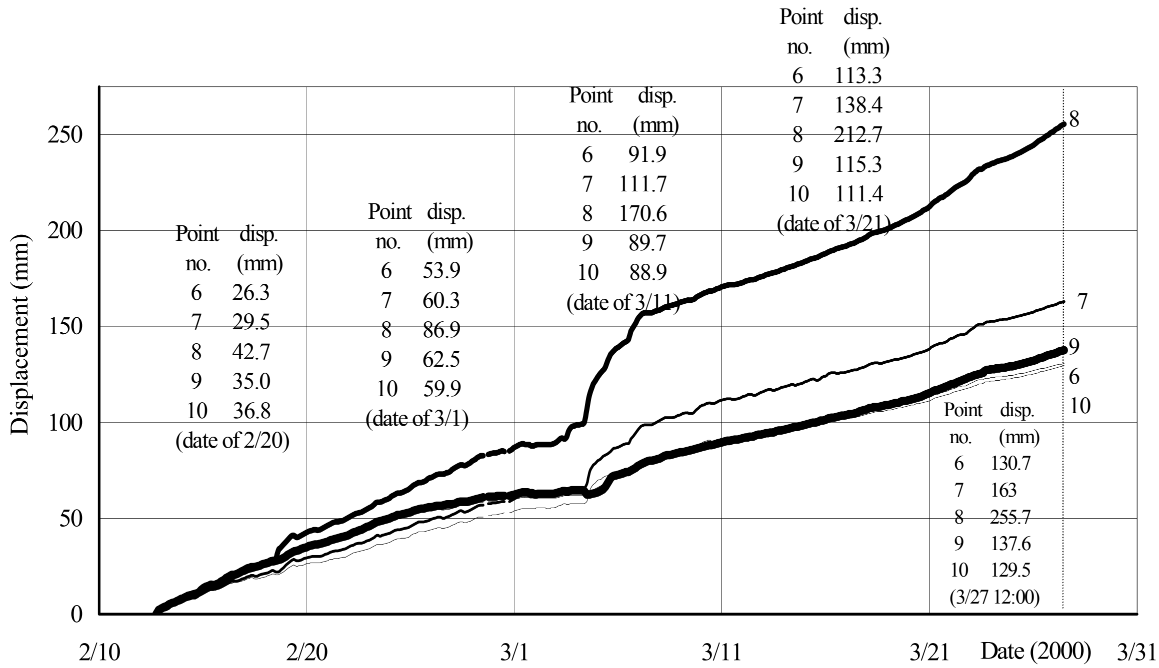

Table 2a. Average temperature (°C).

Period / Location	2/14~ 2/29	3/11~ 3/26	3/4~ 3/7	(2/14~ 3/26)
Outside	-10.9	-6.5	-2.6	-8.0
Inside	-4.7	-2.5	-1.0	-3.4
Ice (34)	-4.5	-1.6	-0.3	-3.0

Table 2b. Average creep displacement (mm/day).

Period / Points no.	2/14~ 2/29	3/11~ 3/26	3/4~ 3/7	(2/14~ 3/26)
(1,2,3,4,5)	3.0	2.5	9.3	3.0
(6,7,9,10)	3.2	2.8	6.7	3.1
8	4.8	5.2	18.6	5.7
(11,12,14,15)	3.5	2.7	8.3	3.3

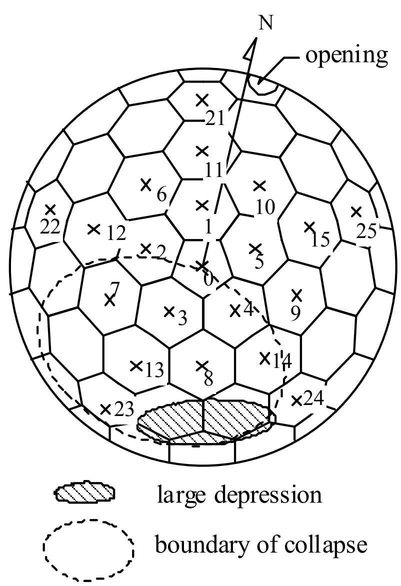

Figure 11. Situation of collapse.

Figure 12. Large deformation right before collapse.

4.3. Field Experiment of 30 m Span Ice Dome

Following the experiments with 20 m span ice domes, a field study involving the construction and creep test of a 30 m span ice dome (25 m base diameter, 9.2 m height and 25 cm average ice thickness) was carried out at the same site of Tomamu during the winter of 2001 (Kokawa 2002a). It took six days to complete the construction including the snow-ice foundation work. Following the construction, a creep test was performed and the structural behavior was examined. It was found that the average displacement rate in the central parts of the dome from February 17 to March 23, was about 6.5 mm/day, and it was shown that the dome had a sufficient structural efficiency.

Figure 13. Inflated membrane.

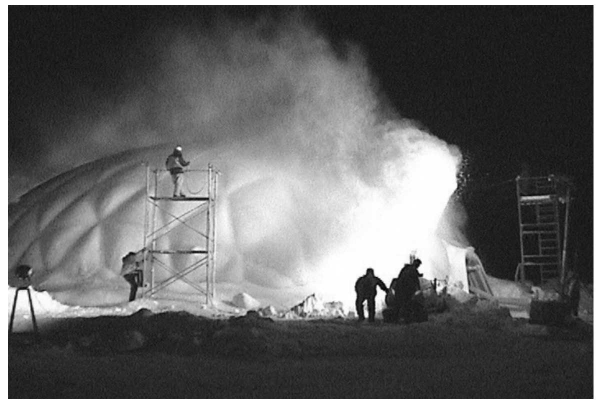

Figure 14. Application snow and water.

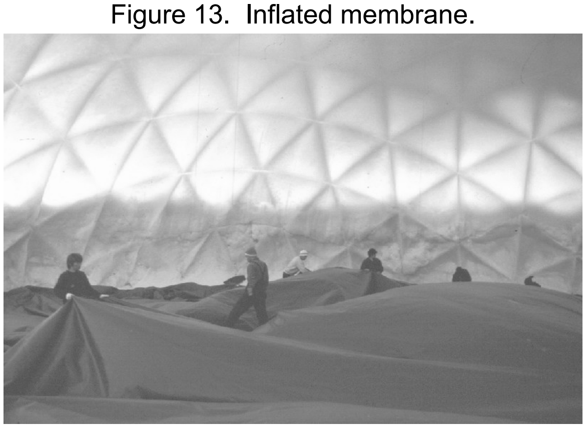

Figure 15. Removing membrane.

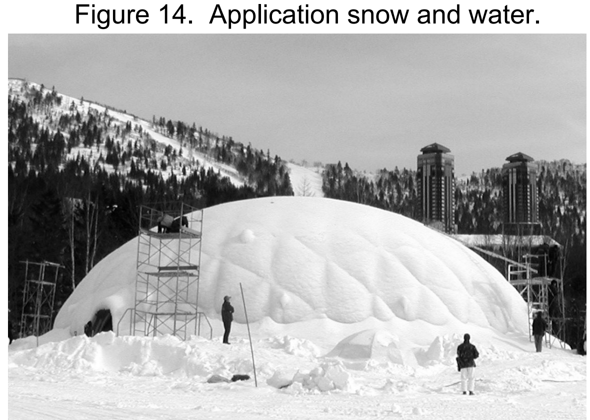

Figure 16. Completion.

4.4. Possibility of 'Ice Pantheon'

Considering the actual construction equipment such as the snowblower and the adjustable nozzle for spraying water, the size of the ice dome may be limited, for now to a 30 m span. However, it would be possible to construct a 40 m span ice dome if the equipment were available. The Pantheon in Rome, constructed in about 120 A.D. is well known as one of the biggest classical stone domes and its base diameter is 43 m (Ruggieri 1995). The ice is easier to manufacture than stone and its strength/density is greater than stone in short term loading, so it should be structurally possible to realize a dome of this size in ice as well as stone. Based on the field experiments of 20-30 metres spanning ice domes mentioned above, the viscosity of the ice is evaluated as 4,000 (kg/cm^2) day and the construction of 40 m span ice dome is made a trial prediction as follows.

- Geometry: 40 m base diameter, 16 m height and 30 cm thickness
- Construction period: 10 days in total (3 days for foundation ring, 1 day for inflation, 5 days for application of snow and water, 1 day for deflation)
- Prediction of creep displacement: 1.7 cm/day (51 cm/month)

5. CONSTRUCTION ON LAKE-SYUMARINAI

The ice shell could be constructed easily at a place where coldness, snow and water can be prepared, even if there are no heavy equipments for construction. It means the ice shell could be utilized at any place as an expedient structure fitting to various winter activities. Nowadays in Hokkaido, a frozen lake has been used as a recreational or a festival area such for snowmobiling, fishing, skating and so on. Fortunately, there is much water for the ice shell construction beneath the ice plate and it may be easy to construct the ice shell on a frozen lake as instant shelters for winter activities.

Lake-Syumarinai is well known as an ice fishing place in Hokkaido. A 10 m span ice dome was experimentally constructed on the lake in the late winter 2004. In this test, the depression difference between inside and outside of the dome was not recognized with eye observation, although the mechanical property of the lake plate seemed to be low. The thickness was about 1 m, but the material was not ice but almost snow. As the lake has much snow every year, the plate is consisted of snow except ice at the bottom. One of the most important engineering problems learned from this experiment is how to improve easily the quality of the lake plate for the structural safety. Snow mobile will be utilized upon the accumulated snow as a way of compacting it into a stronger snow-ice plate.

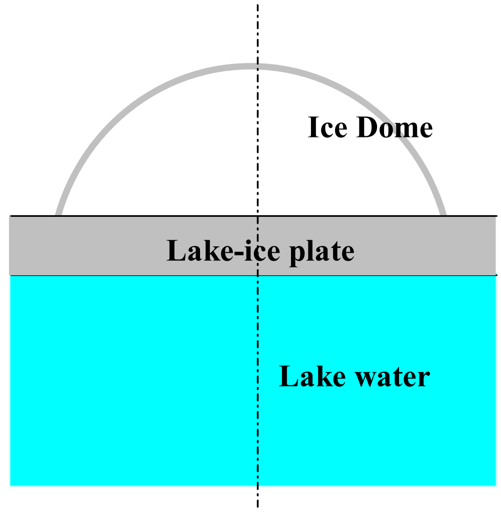

Figure 17. Ice Dome on lake-ice plate.


Figure 18. Application of snow and lake-water.


Figure 19. 10 m ice dome on Lake-Shyumarinai.

And then, two 10 m span test domes were constructed in a place away other at the beginning of February in winter 2005. These construction places had been compacted in advance by using a snow mobile over about 20 m in diameter and the thickness of the ice plate was uniformly about 35 cm just before the dome construction.


Figure 20. Stick for measuring water-level.

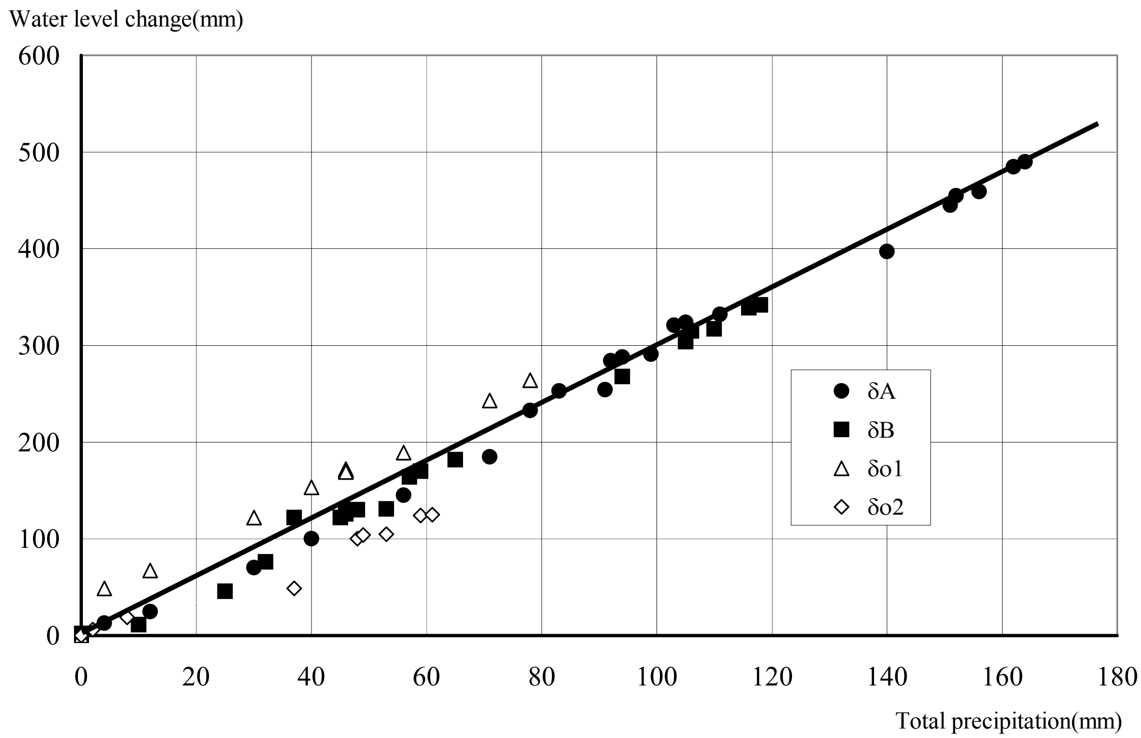

Figure 21. Total precipitation (mm)-Water level change (mm).

After the completion of the dome constructions, three points of water level-change were measured by installing a stick with scale as shown in Figure 20. Two points of them were set up each inside of the dome and one was apart from dome. After it had snowed, it was observed that these points of water level-change were almost same and a flooding took place very slowly inside of the domes. According to the flooding, outer snow was added into the inside for quick freezing of the flooded floor. So, when the experiment ended, the thickness at the inside of domes was both more than 1 m.

The relation between three points of water level-change and total precipitation from meteorological data (http://www.data.kishou.go.jp/etrn/) is shown in Figure 21. Referring to this Figure, it is recognized that three points of water level change are almost same and equal to three times of the total precipitation. It will be necessary to clarify the reason why in the future from the point view of elastic and viscoelastic analysis of ice plate under ring load (Kokawa 2004a).

6. CONCLUDING REMARKS

Snow is a useful material for the construction of ice shells. The construction method of blowing snow and spraying water onto an air-inflated membrane formwork, is very practical. It took only one week to complete ice domes spanning 20-30 metres. The ice shells have a high structural efficiency, because the form is decided automatically under uniform pressure and the membrane stresses are mainly compressive. Furthermore, as the ice is a translucent material, the shell creates a fantastically beautiful space, providing a unique built environment in winter. Large spans can be exciting artistically and useful for various kinds of architectural facilities for winter activity.

The ice shell, concept developed in Hokkaido, should be used in cold regions all over the world.

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