COMPARISON OF KEMI-I AND CONFEDERATION BRIDGE CONE ICE LOAD MEASUREMENT RESULTS

Thomas G. Brown¹ and Mauri Määttänen²

ABSTRACT
A Joint Finnish Industry Project in 1983–87 measured cone ice loads by installing an instrumented cone around Kemi-I lighthouse in the Gulf of Bothnia. A Canadian Academic/Joint Industry Project has been conducting cone ice load measurements since 1997 on two instrumented piers of the Confederation Bridge, in the Southern Gulf of St Lawrence. The diameters of the cones at the waterline are 10 and 14 m respectively. Ice conditions are more severe at Kemi-I but ice movement is faster and more frequent at Confederation Bridge. However, all types of first year ice features have been encountered at both locations. The cone ice load measurements and observations indicate that ice failure patterns and broken floe clearing mechanisms are, in general, similar. Comparisons with reference to ice thickness, temperature, and velocity, are made on: rubble formation, rubble surcharge height, rubble jamming, pressure ridge failure modes, dynamic effects, and measured and predicted ice loads. The results pave the way for a better understanding of ice failure against cones and cone ice load design.

INTRODUCTION
A conical shape at the waterline promotes failure of oncoming ice in bending. Scale-model tests have verified that the resulting ice forces are significantly lower, compared to ice crushing loads. An additional bonus is the almost complete elimination of ice-induced vibrations, especially continuous resonant vibrations. In contrast to a relative abundance of scale-model data, the published full-scale data on cone ice forces is scarce. The first were the Japanese tests at Hokkaido. However the 65° cone was small, with a waterline diameter of only 3 m. The second was the Finnish Kemi-I test cone project, in the Gulf of Bothnia with a 10 diameter cone. The latest is the Confederation Bridge ice load measurements in the Southern Gulf of Lawrence. The measurements are still continuing on two of the 52° bridge piers, each having a 14 m diameter cone at the waterline. In China in the Bohai Sea JZ9-3 field, there are three conical oil and gas production platforms with conical foundations. These structures have 58° cone angles and 28 and 34 m diameters at the top while the waterline diameter varies from 30 to 40 m depending on the structure and tidal cycle. A lot of visual and video observations have been made but the cones have not been instrumented for ice load measurements.

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The Kemi-I test cone measurements were conducted in 1984–1987 and final data analysis was conducted in 1995 in a joint industry project (Tam et al., 1995). Due to industry funding, the data was proprietary to the end of year 2000. The Confederation Bridge cone ice loads measurements started in 1997. These two ice load measurement projects have both common and differing features. Comparing and analysing the results from the two measurement programmes gives a wider view and a more holistic understanding of ice failure against a conical structure. This paper describes the measurement principles, compares ice failure phenomena, presents measured loads in varying first year ice conditions, and verifies ice load design practices.

**INSTRUMENTATION SETUP**

The main dimensions of both Kemi-I and Confederation Bridge conical piers are presented in Fig.1 and Table 1. The Kemi-I cone was a freely floating conical annulus around the lighthouse shaft. In the vertical direction, 8 rubber pillows that had very low horizontal stiffness supported the cone. The neck of the cone transferred horizontal loads through 16 liquid filled rubber bags. The load on each bag was measured from the internal pressure within and the total horizontal load is then the vector sum of the bag loads. In practice the horizontal load measurements appeared to be reliable but vertical loads could not be resolved from the vertical deformation of rubber pillows. Additional instrumentation included 96 strain gauges in the cone steel plating, accelerometers at +3 and +13 or +23 m level, and total lighthouse shaft bending moment measuring rods. The strain gauges were used to verify the cone structural integrity, not for indirect calculation of ice loads. The sensitivity of the moment sensing rods was inferior to the horizontal load measurement from the rubber bags.

At Confederation Bridge, the ice load is not measured directly, but the tilt and acceleration response of the two instrumented piers is measured. The tilt response is then used to determine the corresponding ice load using a transfer function derived from a full-scale load test (Brown, 1997). The tiltmeters and accelerometers are placed at +3.2 m and +24.6 m.

**ICE AND ENVIRONMENT**

First year ice conditions prevail both in the Gulf of Bothnia and in the Southern Gulf of St Lawrence. Typically ice formation at the Kemi-I location starts at the end of
November, and ice melts away at the end of May. Kemi-I is in the open sea, 40 km from ashore, and about 20 km beyond the land-fast ice border. Even though ridges — up to 3 to 4 ridges per km — frequently divide the ice field, uniform level ice fields can extend over 10 km. All typical first year ice features are present: level ice, rafted ice, and pressure ridges. The thickness of the consolidated layer of pressure ridges depends on the age of the ridge. Ice movements are frequent and controlled by wind directions. There is no tidal current, the only current being in conjunction with minor water level changes due to storm surges. Most of the time, virgin ice is interacting with the cone, even though the cone occasionally interacts with old refrozen paths.

Table 1: The main dimensions

<table>
<thead>
<tr>
<th></th>
<th>Kemi-I</th>
<th>Confederation Bridge Pier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cone angle (°)</td>
<td>56</td>
<td>52</td>
</tr>
<tr>
<td>Neck diameter (m)</td>
<td>6.8/3.9*</td>
<td>9.7/7.8#</td>
</tr>
<tr>
<td>Waterline diameter (m)</td>
<td>9.9</td>
<td>14.1</td>
</tr>
<tr>
<td>Bottom diameter (m)</td>
<td>17.0</td>
<td>20**</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>12**</td>
<td>19/21</td>
</tr>
<tr>
<td>Surface material</td>
<td>Steel</td>
<td>concrete</td>
</tr>
</tbody>
</table>

* after rubble filled the shelf extending apparent cone surface to +4.4 m level  
** the cone ends on top of a 26 m diameter caisson at –5.5 m level  
*** the cone ends at –4 m below which it is supported by a 10 m diameter cylinder.  
# top of 52° cone/top of 78° cone.

Table 2: Ice conditions during measurements

<table>
<thead>
<tr>
<th></th>
<th>Kemi-I</th>
<th>Confederation Bridge Pier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum level ice (m)</td>
<td>0.86</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum rafted ice (m)</td>
<td>1.5</td>
<td>n.a.</td>
</tr>
<tr>
<td>Maximum ridge keel (m)</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Maximum consolidated layer (m)</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Maximum floe size (km)</td>
<td>&gt;10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Minimum air temperature (°C)</td>
<td>–28</td>
<td>–23</td>
</tr>
<tr>
<td>Degree days (°C*day)</td>
<td>1583</td>
<td>472</td>
</tr>
<tr>
<td>Maximum wind (m/s)</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>Maximum sea current (m/s)</td>
<td>&lt;0.1</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Highest water level (m)</td>
<td>+0.6</td>
<td>+1.2</td>
</tr>
<tr>
<td>Lowest water level (m)</td>
<td>–0.4</td>
<td>–1.05</td>
</tr>
<tr>
<td>Water salinity (%)</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Ice flexural strength (MPa)</td>
<td>0.46 (–10 °C)</td>
<td>0.39 (–5°)</td>
</tr>
<tr>
<td>Ice crushing strength (MPa)</td>
<td>5.5 (–10 °C)</td>
<td>3.4 (–10 °C)</td>
</tr>
</tbody>
</table>

At Confederation Bridge the ice forms in late December to early January, and is usually gone by late April. At the bridge location, the Strait is only 13 km wide, and the fast ice extent is at most several hundred meters. The ice cover is very deformed, although the ridge frequency is similar to that in the Gulf of Bothnia, 3 to 4 ridges per km. However, there are extensive areas of first year rubble fields that can extend for many kilometres. Except for early in the season, uniform level ice fields are rare. At the bridge location,
the current is dominated by semi-diurnal tidal effects that result in very extensive, continuous, ice motion at the bridge site. Each pier encounters approximately 4000 km of ice each winter. However, much of this ice has already passed the axis of the bridge, and has therefore been sieved. There is a net current through the Strait that results in virgin ice encountering the bridge during each tidal cycle. The average climate at Gulf of Bothnia is colder, cf. ice thickness and degree-days in Table 2.

ICE FAILURE MECHANISMS

The first Kemi-I cone observations in winter 1984/85 indicated that ice bending failure against the cone is different from that identified in textbooks, or from scale-model tests. The striking feature was the prevalence of rubble pile-ups. Also the size of the broken ice pieces was significantly smaller than predicted by bending failure theories. Similar ice failure features repeated themselves on the Confederation Bridge pier cones. Sustained rubble piles are one common characteristic of all ice sheet interactions with both the Kemi-I and Confederation Bridge cones. The Japanese have not reported rubble formation in front of their cone. The reason may be due to the steep cone angle of 65°, and small, 3 meters diameter, that does not favour rubble formation.

In all reported scale-model tests, the oncoming ice sheet breaks in bending where after broken pieces ride-up the cone surface as a single layer and slide sideways down to clear the cone. The reason for the difference in the full-scale behaviour is believed to be due to ice surface friction. In scale-model testing, most of the scaling requirements can be met with the newer, doped, ice, however, it is very difficult to model the friction between rubble pile and ice surface. In full-scale there is snow on top of the level ice most of the time, and the ice surface itself is seldom smooth. The snow adheres to the ice surface and increases friction to an extent that is hard to reproduce in scale-model tests. In rare instances with Kemi-I, when no snow was present and ice was moving slowly, ice slid up the cone in a single layer. The same was also witnessed at Bohai Sea conical oil production platforms JZ9-3 where 10–20 cm thick ice, with no snow, kept failing in bending and climbing up in a single layer, even though the ice velocities were from 0 to over 0.5 m/s. At Confederation Bridge, level ice with a wet surface (from rain) would only support a rubble pile with a very shallow angle of repose.

Rubble pile

During Kemi-I measurements the highest ride-up was to the 8.8 m level in conjunction with a grounded pressure ridge. Ungrounded pressure ridge increased the pile-up height only slightly but the ride-up extent increased significantly. Measurement data on ungrounded ride-up height indicates an empirical relation:

$$H_r = 3 + 4h_{ice}$$

(1)

Even thin ice can climb relatively high along the cone. Measurement data indicates ride-up heights from 3.6 to 6.6 m levels for 0.10 to 0.90 m thick ice. E.g. measurement data points indicate ride-up height for 0.10 m ice to be 3.7 m, for 0.30 m ice 4.6 m, and for 0.40 m ice, from 3.7 to 4.6 m. With 0.50 ice, ride-up was up to 5.9 m level. The angle of repose was measured to be from 25° to 50° with an estimated average of 40°. The angle of repose did not have evident dependence on ice thickness or ambient air temperature.

At Confederation Bridge, pile-up heights typically reach a maximum of 6 m while ride-up to 7.5 m has been recorded. Grounded rubble never occurs. As at Kemi-I, maximum rubble pile heights depend on the ice thickness, although a power law of the form
\[ H = 7.6h^{0.64} \]  \hspace{1cm} \text{(2)}

has been found to fit the data. Many rubble piles, however, do not achieve these heights, depending on the absence of snow and the ice speed. Ice speed was found (Mayne and Brown, 2000) to have some effect on maximum rubble pile heights, with the height declining with increasing speed, according to the relation:

\[ H = -3.12v^2 + 2.07v + 7.09 \]  \hspace{1cm} \text{(3)}

The angles of repose varied from 15° to 70°, with the majority in the 30° to 50° range. The lower angles were associated with wet, snow-free, surfaces. Stable rubble piles that were at, or close, to the maximum height, had a bi-linear profile. Similar to the behaviour at Kemi-1, the advent of a ridge often had little effect on the rubble height, causing a small surge in the height and lateral growth of the rubble pile. However, ride-up of the consolidated layer often had the effect of completely removing the rubble pile.

Three-dimensional FEM-simulation (Määttänen and Hoikkanen, 1990), predicts lower ride-up height than has been measured by Kemi-I test cone. However, by adjusting friction and ice bending strength it is possible to get ride-up heights as high as those recorded. Estimates of rubble height based on two-dimensional theory (Nevel, 1983) appear to be far too low. Broken ice pieces first climb up the cone surface under the rubble, Fig. 2. At the topmost location they roll back down but also sideways in relation to the ice movement, guided by the steepest slope of rubble pile. In some instances, especially with big rubble formations, there is a hump in the profile, leading to the bi-linear profile. Ice pieces first fall steeply from the top of the rubble and, due to inertia, roll further out on a shallower slope on their way down to the level ice. From above the rubble looks like an inside-out winding horseshoe shape in which ice pieces gradually move, first sideways, and later backwards.

![Figure 2: Broken floe path in rubble pile](image)

The highest point of the rubble is dominantly at the stagnation point, on the line of symmetry. The height decreases, first gradually, and then more abruptly, towards the sides of the rubble horseshoe. The circumferential extent of rubble is about 100° from the line of symmetry.
The rubble normally cleared the cone and slid down into the broken channel. Only a few pieces were left on the edges of the channel, which was only slightly wider than the diameter of the cone at the waterline. Intermittently the rubble pile collapsed completely by sliding forward down the cone surface into water. The reason for this is uncertain, either the weight of the rubble breaks the level ice downwards, or the collapse starts after the circumferential crack has formed, due to normal cone ice bending failure.

**Rubble size**
The bending failure theory predicts the ice sheet to fail first by radial and thereafter by circumferential cracks. The location of circumferential cracks controls the initial rubble size. However, the initial rubble size was much smaller than predicted from flexural failure theories, with the average piece size being only 1–2 times the ice thickness. In addition to this there was a great deal of small pieces, starting from millimetre size. Evidently, in addition to bending, other failure mechanisms are present. The rubble pile has some effect in decreasing the radius of the circumferential failure (Määttänen, 1986) and with a stable rubble pile, the circumferential crack is seldom visible. Local crushing does occur at the edge of oncoming ice sheet to enlarge the contact area sufficiently to develop the loads necessary to cause major ice sheet failure. Uneven contact promotes local ice shearing failure or splitting. Global ice edge shearing failure can occur before bending failure with thick ice (Määttänen, 1994), and may be a significant factor with thin ice, with large rubble piles. The measurement data proves that cone ice loads are less than those predicted by bending theories. It has been suggested that the advent of a rubble pile will result in ice failure by crushing. While the rubble pile clearly affects the ice failure process, the measured loads are too low to support the suggestion that global crushing of the ice sheet occurs.

**Rubble jamming**
Normally the rubble pile ahead of the incoming ice was always active: ice pieces climbing up and rolling down. Once at Kemi-I location, early in the winter with low air temperatures at about −20 °C, thin ice, 5 to 10 cm thick, adhered to the cone steel surface, froze together, and formed a consolidated block — a false bow — in front of the cone. The size of the block was about 2 m thick and extending about 3 meters ahead. Subsequent ice failure occurred against the block, or underneath so that broken floes bypassed under the waterline. It was not possible to see the actual ice failure mode. At Confederation Bridge, similar behaviour has been noted, although adfrozen ice tends to be above the active failure zone, that is, it extends upward from +1 m above the waterline and does not affect the ice failure process. Adfrozen ice only occurs at temperatures below about −12 °C.

**Pressure ridge failure mode**
The failure mode of a pressure ridge is such that the uplifting effect of the cone easily dislodges the ridge consolidated layer. The resulting ride-up can be quite significant in height, but is not uniform across the cone, presumably because of the inhomogeneity of the consolidated layer. Thereafter the clearing mechanism is similar to that of level ice. As soon as a pressure ridge keel hits the cone surface the unconsolidated rubble is being squeezed between the cone and the consolidated layer above. This causes uplift loads that break the consolidated layer in bending mode, first by a radial crack and later by a circumferential crack. Radial cracking could be seen to propagate over 5 m in front of the cone. The rubble pile height in front of the cone increased only slightly in
conjunction with a pressure ridge but the rubble pile horizontal extent increased significantly. When the ridge keel was deep enough to ground on top of the caisson or on the sea bottom the height of rubble pile at Kemi-1 increased up to 50 % above the normal height. At Confederation Bridge, the cone extends to −4 m, below which, the pier is supported by a 10 m diameter cylinder. The interaction between the unconsolidated rubble in the keel and this cylinder is uncertain, but the evidence (Lemee and Brown, 2002) indicates few physical contacts between the rubble and the cylinder, suggesting that the unconsolidated rubble is being disturbed by the leading edge of the cone, and being cleared round the cylinder by hydrodynamic effects.

After the ridge had passed, the weight of the rubble was generally more than the level ice could carry. Hence the level ice broke downwards and the rubble pile collapsed, clearing the cone surface. Calculations indicate that 0.8 m thick level ice can carry 1.8 MN vertical load which corresponds to about 300 m³ rubble volume. The maximum rubble volume at Kemi-I was 1070 m³ and there were many cases with over 500 m³ rubble volumes. This indicates that all the largest rubble piles must have been grounded.

**Dynamic effects**

Accelerometers in Kemi-I lighthouse recorded low transient vibrations. Maximum accelerations were below 0.6 m/s² and decayed usually in less than 5 cycles, Fig. 3. It was concluded that these accelerations were related to ice bending failure events. Continuous vibrations were neither recorded nor observed while the cone was present. Earlier, before the cone was installed, resonant vibrations were recorded at 2–3 Hz range.

![Figure 3: Measured typical Kemi-I acceleration response. (Time scale seconds)](image)

**CONE ICE LOADS**

Cone ice load prediction models initially assume radial cracks propagating into the oncoming ice separating the solid level ice into wedges. The wedges fail in bending with the onset of circumferential cracks. Thereafter the broken ice pieces ride-up and bypass the cone. Loads in each stage are calculated, but usually, the circumferential bending failure load and the broken rubble clearing loads are assumed to occur simultaneously. The rubble effect can be modelled by increasing the ride-up thickness, or more accurately by using FEM discretization for the wedges. Croasdale and Cammaert (1993) have included a two-dimensional model for the effects of ice rubble on flexural failure. The most widely used, and easiest to use, method is by Ralston (1977), who assumes plastic limit analysis as failure criteria. Other models use elastic bending failure criteria. All assume the failure in all wedges to occur simultaneously.
Full-scale observations indicate that in some cases this assumption is valid but sometimes also uncorrelated wedge or ice edge failures are occurring.

**Level ice loads**
Comparison of Kemi-I measurement data and ice load predictions proved that Ralston’s model generally overestimates the cone ice loads, Fig. 4. More refined later models, e.g. FEM (Määttänen and Hoikkanen, 1990) and Nevel (1992), result in slightly less over-prediction and better fit to measurement data, (Tam et al., 1995).

![Figure 4: Kemi-I cone measured vs. predicted horizontal ice load (MN), Ralston’s method.](image)

**Pressure ridge loads**
In the case of pressure ridges the ice load increases due to the consolidated layer and the keel. The consolidated layer is significantly thicker than the parent ice, and often includes rafted ice. Maximum rafted ice at Kemi-I location was 1.5 m thick in conjunction with a ridge in 0.8 m thick level ice. Even though the bending strength of rafted ice is less than the original level ice, the ice bending failure load can increase significantly. For ridge keel loads against a conical structure there is no generally accepted calculation method. Dolgopolov et al. (1975) assume constant diameter. Hansen’s (1961) pile soil resistance method can be applied to ridge keel loads. If the cohesion is modified to decrease linearly to zero at the bottom of the keel, the results are similar to Dolgopolov’s method.

Kemi-I ridge load analysis has not been done previously. A comparison is made of events on March 22, 1986 for a ridge with 0.80 m thick level ice and 1.30 m thick rafted ice. Measured horizontal cone loads were 2.1 and 4.0 MN. Using a bending strength 0.50 MPa and a coefficient of friction of 0.10, Ralston’s model predicts a level ice load of 1.7 MN. Considering a 20 % over-prediction in Ralston’s method the contribution of the keel load is then 0.7 MN. For the rafted ice, the bending strength is reduced to 0.40 MPa. The corresponding Ralston prediction is 3.7 MN, and the ridge keel load is then 0.9 MN. Using the Hansen method, with a cohesion 5 kPa and rubble internal friction angle of 30°, 5.5 m and 12 m deep keels cause 2.5 MN and 10.1 MN loads. For the latter the keel load contribution of 6.2 MN above the –5.5 m level is only relevant for measurement comparisons. On March 23, 1986 two events with 80–85 cm thick level ice together with ridges occurred, resulting in 4.6 MN total horizontal load on the cone. If the consolidated layer effect is removed, the keel load would be less than 3.2 MN. There was no means to measure the keel depth. Hansen’s model with a 6.5 m deep keel would result in a 3.2 MN keel load. The maximum Kemi-I ice load, 7.1 MN, occurred as a stationary pressure ridge, with 9 m high grounded and consolidated rubble.
pile, started to move. Hansen’s model keel load would be 6.2 MN. Only 0.9 MN is left over for consolidated layer bending and rubble clearing loads.

Figure 5: Ridge Loads on Confederation Bridge

Figure 5 summarises the total loads for ridge impacts for one year of the Confederation Bridge monitoring programme. Two different events are identified. Event 2641, the highest recorded load for 1998 at 4.25 MN, occurred on April 11\textsuperscript{th} when a floe that consisted essentially of a consolidated rubble field encountered the P31 pier. The total ice depth was 4.7 m with a 0.7 m consolidated layer. A rubble pile that included significant ride-up pieces formed to a height of 4.5 m at an angle of 40\degree. Using the Croasdale flexural failure model, the flexural load, including rubble pile, is estimated to be 2.23 MN, which leaves a rubble contribution of ~2 MN. This does not seem unreasonable. In contrast, event 1908, occurred on March 23\textsuperscript{rd}, and was associated with a load of 2.5 MN, even though the ridge had a keel depth of 13.2 m and a consolidated layer thickness of 1.2 m. The event was associated with ride-up of some very large blocks, 1.2 m thick. The theoretical flexural failure load is then 4.2 MN, which is considerably in excess of the total measured load of 2.5 MN, indicating no contribution from the keel. The flexural failure load is certainly over-estimated, both as a result of model error, but also because the consolidated layer is very inhomogeneous, and does not fail in the classic radial/circumferential crack pattern.

All these measured keel loads in relation to predictions indicate that ridge loads in full scale are significantly less than earlier anticipated. The observation of rising underwater rubble lifting the consolidated layer, enhancing bending failure and dislodging adhered floes is efficient in reducing pressure ridge loads.

DISCUSSION

Similarities

The observations from the two full-scale programmes are remarkably similar, despite the quite different ice regimes present. This is particularly true of the observations with respect to the flexural failure of level ice, and the associated rubble pile. There are
significant similarities in rubble geometry and rubble dynamics: intermittent collapse of rubble piles has been noted at both locations.

The forces from flexural failure of level ice, measured at both locations, are lower than the results from generally accepted models. This over-prediction is perhaps a little surprising, because, while the models do account for ride-up, they generally do not account for a fully developed rubble pile. Both sets of observations agree that the circumferential crack, which should occur well away from the cone, is seldom visible beyond the rubble pile. There are also similarities in the observations with respect to ridge interactions. Again, the measured loads are much lower than those predicted by analytical models.

**Differences**
The primary differences in the observations arise from the differences in the ice conditions at the two locations, and the water depths. At the Gulf of Bothnia the climate is colder, and water salinity lower, providing higher ice strength. An opposing factor is lower ice drifting velocity and less ice movement. At Kemi-1, rubble grounding does occur and this can lead to increased rubble pile heights and sizes, and the associated clearing loads. Grounded rubble does not occur at the instrumented Confederation Bridge piers. At Kemi-1, the ice cover tends to be more compact and pressured, while at Confederation Bridge, the pack is more open and dynamic, partly because the five years of observations have all been light ice years.

**CONCLUSIONS**
The two different sub-arctic full-scale cone ice load measurement projects show consistently similar ice failure phenomena, small broken ice piece size, rubble pile formation, surcharge height, and rubble clearing mechanisms.

The measured cone ice loads have been systematically lower than what generally accepted theories predict regardless of the increasing effect of rubble pile. Multi-modal ice failure is needed to explain the small broken pieces.

Pressure ridge failure mode is similar in the two locations: the consolidated layer breaks easily in bending mode while being pushed up by the rubble in the keel. Ridge keel loads have been considerably lower than theoretical predictions.

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