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DYNAMIC LIVE LOADS AT A ROCK CONCERT

by G. Pernica

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RÉSUMÉ

Pendant un concert de rock de 3 h tenu dans une aréna, on a effectué des mesures des vibrations pour déterminer l'effet des réactions de l'auditoire sur le comportement dynamique d'une surface ayant une fréquence fondamentale inférieure à 5 Hz. Cette surface, qui reposait sur des poutres préfabriquées en béton précontraint, était soumise périodiquement à des battements de pieds et de mains à des fréquences de répétition comprises entre 2 et 3 Hz.

On trouvera une présentation des phénomènes de résonnance et de quasi-résonnance qui en ont résultés: des surcharges dynamiques ont été calculées et comparées, ainsi que les surcharges statiques, aux valeurs de calcul prescrites dans le Code national du bâtiment.

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Dynamic live loads at a rock concert

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Vibration measurements have been taken in a sports arena during a 3 h rock concert to determine the effect of audience response on the dynamic behaviour of a stand area having a fundamental frequency below 5 Hz. The stand area, consisting of precast, prestressed concrete beams, was subjected to intervals of foot stamping and hand clapping at repetition frequencies between 2 and 3 Hz.

Amplitudes of the resulting resonant and near-resonant behaviour are presented; dynamic live loads are calculated and together with static live loads are compared with design loads specified in the National Building Code of Canada.

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Introduction

Sentence 4.1.6.3(1) of the National Building Code of Canada (1980*a*) specifies a static live load of 4.8 kN/m^2 (100 psf) for the design of floors or stands in active assembly areas such as arenas or stadia. Although this value has not changed over several decades, floor systems designed to support such loads have changed. Floors have become lighter and more flexible with the introduction of higher strength materials, increased spans, and improved design and analysis techniques. It is not uncommon today for existing floors or stands in active assembly areas to have fundamental frequencies less than 5 Hz and to weigh less than 4.8 kN/m^2 (100 psf). Unfortunately, such floors are susceptible to resonant or near-resonant behaviour as a result of audience response during musical performances and sporting events. Audiences can easily produce rhythmic, impulsive forces with repetition frequencies in the 1–3 Hz range by foot stamping or hand clapping in time to music at a concert or in unison with cheers at a sporting event. Such forces can last several minutes and in floors possessing low fundamental frequencies can cause a build-up of vibrations that could conceivably result in damage to the structure. Because of this possibility, Commentary A on Part 4 of the National Building Code of Canada (1980*b*) has recommended since 1975 that fundamental frequencies less than about 5 Hz be avoided for the design of floors in active assembly occupancies. Nevertheless, it is not always possible for the designer to adhere to this recommendation because of economic and architectural constraints. When these constraints are present, it might be prudent to assume a larger live load in design in order to account for substantial increases that might occur in the dynamic component of the live load as a result of resonant or near-resonant behaviour. Unfortunately, there is little information available on the magnitude of these dynamic effects (Irwin 1981). Until there is, it will be extremely difficult, if not impossible, to assess the adequacy of the 4.8 kN/m^2 (100 psf) design live load for each active occupancy structure that possesses a low fundamental frequency.

This paper gives further information on these dynamic effects. The magnitude of dynamic live loads and the amplitudes of resonant and near-resonant behaviour during a single rock concert at a sports arena are presented for one stand area having a fundamental frequency below 5 Hz.

The study was undertaken at the instigation of the owner, who wished to determine whether some of the concrete beams comprising the lower stands (Fig. 1) were being severely stressed by audience response during rock concerts. The beams supported rows of steel-framed wooden seats with backs, and in turn were supported by concrete shear walls. During the previous year the arena had experienced a large increase in the number of rock concert performances. For most of them, hand clapping and foot stamping in unison by the entire audience to songs having a very pronounced and easy to follow beat had produced motions within some sections of the lower stands that were not only readily felt by arena personnel but were also visible to the naked eye. This suggested that the audience had produced and could readily produce resonant or near-resonant behaviour within the concrete beams comprising the lower stands. With the hope of recording and witnessing such dynamic behaviour, vibration measurements were taken at the next rock concert performance. Arena staff commented after the performance that the concert had produced one of the largest sets of stand vibrations they had ever felt or seen; the performance had also attracted one of the largest audiences ever to witness a rock concert at the arena.

Stand description

Vibration measurements were taken in a section of the lower stands adjacent to the arena playing surface

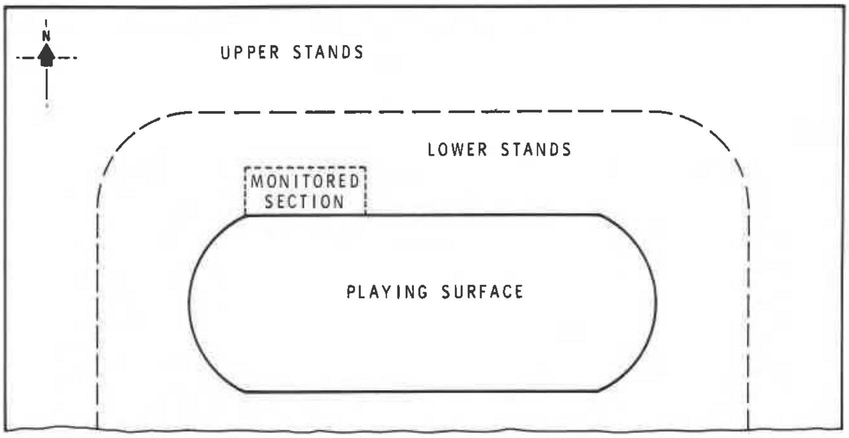

FIG. 1. Plan view of areas.

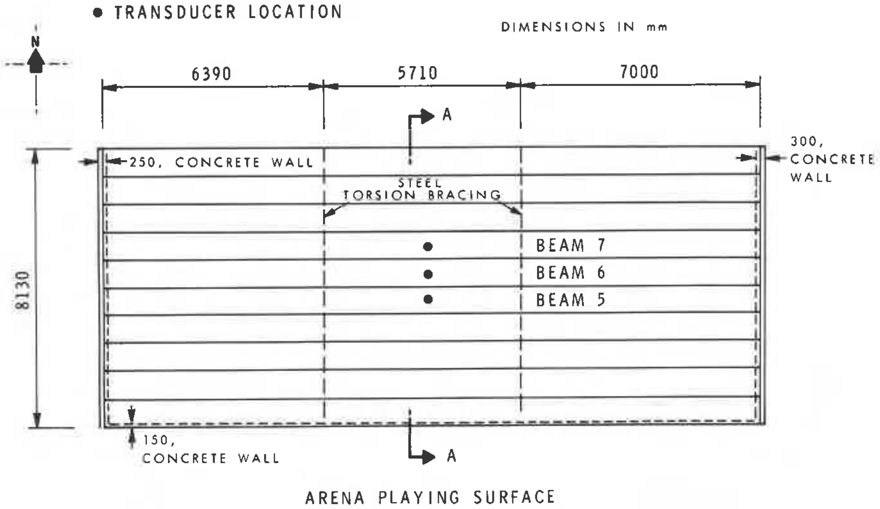

FIG. 2. Structural layout of monitored section of lower stands.

(Fig. 1). The 10 simply supported, precast, prestressed concrete beams in this section have a clear span of 18.8 m (61 ft 9 in.) between cast-in-place concrete shear walls (Fig. 2) and a cross section as shown in Fig. 3. The asymmetrical concrete beams are restrained from twisting during bending at two locations (Fig. 2) by steel bracing (torsion bracing) whose configuration is shown in Fig. 3.

Measurement procedure and data analysis

Measurements were taken at the mid-span of three consecutive concrete beams (beams 5, 6, and 7) by means of accelerometers fastened to the underside of the beams (Figs. 2 and 3). Measurements were taken in the vertical direction on all three beams and in the horizontal direction perpendicular to the span direction on beam 7, which is the farthest of the three beams from the arena playing surface. Outputs from the accelerometers were appropriately amplified and low-pass filtered at 50 Hz before being recorded on a four-channel tape recorder. The vibrations of the beams were continuously recorded throughout the 3 h rock concert. During this time approximately 25 songs were played to an audience that for the most part remained seated even during sessions of foot stamping and hand clapping. For most of the concert the monitored section of the lower stands was completely full of people, including the aisles, which were used by the audience as additional prime seating space close to the performers.

The accelerometer records were displayed on an oscillograph in order to obtain a complete visual record of the vibrations of the beams during the 3 h concert.

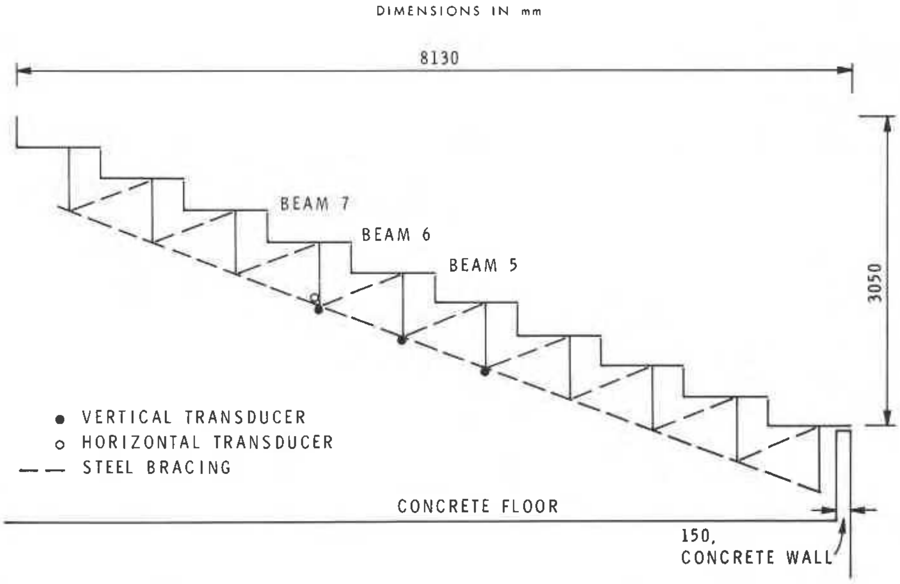

FIG. 3. Section A-A through lower stands.

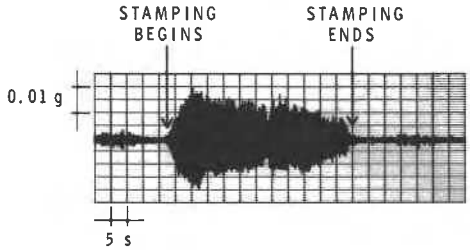

FIG. 4. Time history of vertical accelerations on beam 7 during song 1.

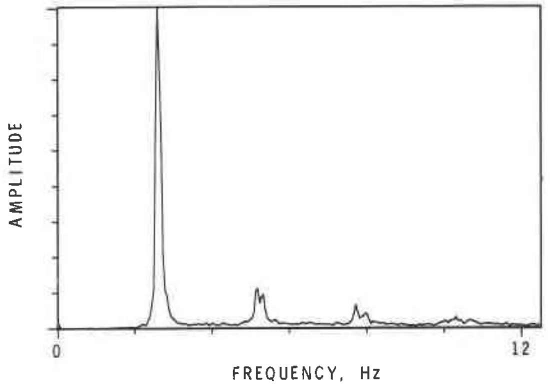

FIG. 5. Fourier amplitude spectrum of vertical accelerations on beam 7 during song 1.

Except during songs accompanied by foot stamping and hand clapping, peak vibration amplitudes rarely exceeded 1% *g*. On the other hand, those produced by stamping/clapping continuously exceeded 1% *g*. Stamping/clapping records that were continuously larger than 2% *g* for 30 s or more were analysed on a spectrum analyser. The same records were then low-pass filtered at approximately 1.5 times the most dominant spectral frequency (repetition or stamping frequency) and re-displayed on the oscillograph using an expanded time scale in order to obtain for each transducer the maximum peak amplitude of vibration at the stamping frequency and the number of occurrences or cycles of peak vibration amplitudes in 5% *g* acceleration intervals.

A typical time history of the vibrations produced by stamping/clapping is given in Fig. 4. Only the envelope of the peak amplitudes is evident because of the compressed time scale. Figure 5 contains the Fourier amplitude spectrum of this record. The dominant spectral frequency, 2.60 Hz, is the stamping frequency; the smaller spectral peaks occur at the harmonics. A segment of the time history, low-pass filtered at 1.5 times the stamping frequency, is shown in Fig. 6 using an expanded time scale.

Vibrations produced by random audience movement during calm periods, for example during intervals between songs, songs without foot stamping or hand clapping, were also analysed in a spectrum analyser to determine the natural frequencies of this section of the lower stands under full live load.

Results

Spectra of vibrations recorded during calm periods suggest that there are four modes with frequencies less

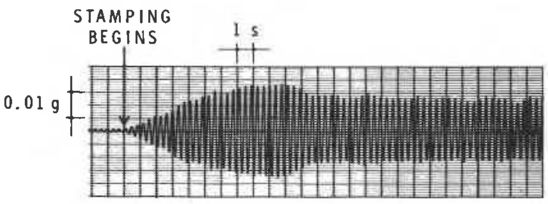

FIG. 6. Time history of vertical accelerations on beam 7 during song 1 low-pass filtered at 4.0 Hz.

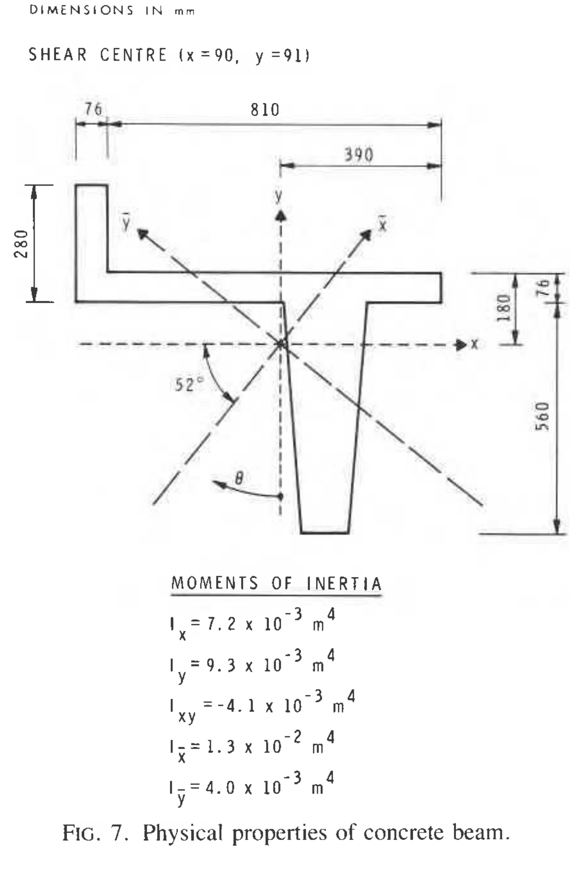

FIG. 7. Physical properties of concrete beam.

than 3 Hz: 2.38, 2.58, 2.73, and 2.97 Hz. Each of the four modes appears, from results obtained from beam 7 (magnitude and phase of vertical and horizontal motions), to be associated primarily with bending about the weak principal centroidal axis, $\bar{y}$ (Fig. 7). Mode shapes for the lower stands could not be determined from existing experimental data. Neglecting torsional effects and assuming (1) that the beam is simply supported at the shear walls, (2) that the concrete modulus of elasticity is 3.7×10^4 MPa (5.3×10^6 psi), and (3) that each seat is occupied, the calculated fundamental bending frequency about the weak centroidal axis is 2.2 Hz. Dimensions, moments of inertia, principal centroidal axes, and the location of the shear centre of the asymmetrical concrete beam are given in Fig. 7.

Foot stamping and hand clapping during seven songs produced peak vibration amplitudes (at the stamping frequency) that continuously exceeded 1% *g* for 30 s or more. Table 1 contains the stamping/clapping frequency and the maximum peak mid-span accelerations at the stamping frequency recorded on beams 5, 6, and 7 during each of the seven songs. Maximum peak accelerations for each song occurred simultaneously. These results together with phase relation obtained from the visual oscillograph records suggest that, at the stamping frequencies, the dynamic shape of the monitored section of the lower stands perpendicular to the beam direction is dish-shaped and symmetrical about the two central beams (beams 5 and 6), with maximum movement occurring at the two central beams.

During one of the seven songs, song 6, the stamping frequency coincided with the fundamental frequency to produce the maximum peak accelerations recorded during the concert: for beam 7, 27% *g* in the vertical and 17% *g* in the horizontal directions at 2.37 Hz. These accelerations would be considered "extremely unpleasant" to "intolerable" on the Dieckmann K-value scale and from ISO 2631-1974(E) (International Standard ISO 2631-1974(E), 1974) have an "exposure limit" of about 2 h. During the same song, peak vertical and horizontal accelerations at 2.37 Hz continuously exceeded 5% *g*, the unpleasant range on the Dieckmann scale, for well over 1 min. From the build-up rate and the decay rate of the resonant response for the three beams the fundamental damping ratio of this section of the lower stands (with all seats occupied) was estimated to be 4.5%.

Maximum peak vertical and horizontal accelerations for beam 7 are repeated in Table 2. Angle θ (Fig. 7) of the resultant maximum motion, measured clockwise from the negative *y*-axis, is shown in Table 2, rounded to the nearest 0.5 deg. For the seven songs shown in Table 2, θ falls between 24 deg, the value calculated for a static uniformly distributed load applied vertically to the beam through its shear centre, and 38 deg, the value calculated for pure bending about the weak centroidal axis, $\bar{y}$. This result, together with the slight variation of θ with stamping frequency, suggests that although most of the motion of the beam is associated with bending about the $\bar{y}$ axis, pure bending about the $\bar{y}$ does not take place even at resonance (song 6).

The number of occurrences (cycles) of peak vertical and horizontal accelerations in 5% *g* acceleration intervals for beam 7 are also given in Table 2. Although the majority are for accelerations less than 5% *g*, as one would expect, there are over 315 occurrences of beam accelerations greater than 10% *g* and over 65 occurrences greater than 20% *g*, all at frequencies below 3 Hz.

TABLE 1. Maximum peak mid-span accelerations recorded on beams 5, 6 and 7

Song	Stamping frequency, Hz	Maximum peak mid-span acceleration, % g			
		Beam 5, vertical	Beam 6, vertical	Beam 7	
				Vertical	Horizontal
1	2.60	1.7	1.7	1.6	1.0
2	2.83	2.3	2.4	2.3	1.5
3	2.50	13.	12.	12.	8.0
4	2.47	15.	15.	14.	9.4
5	2.44	15.	15.	14.	9.2
6	2.37	30.	29.	27.	17.
7	2.03	2.7	2.7	2.5	1.6

TABLE 2. Peak vertical and horizontal mid-span accelerations on beam 7

Song	Stamping frequency, Hz	Maximum peak mid-span acceleration		θ, deg	Acceleration interval, % g	Number of occurrences (cycles)	
		Vertical, % g	Horizontal, % g			Vertical	Horizontal
1	2.60	1.6	1.0	33.0	1–5	80	5
2	2.83	2.3	1.5	33.0	1–5	165	105
3	2.50	12.	8.0	33.5	1–5	80	140
					5–10	190	165
					10–15	35	
4	2.47	14.	9.4	34.5	1–5	25	40
					5–10	65	125
					10–15	75	
5	2.44	14.	9.2	33.5	1–5	180	265
					5–10	215	170
					10–15	40	
6	2.37	27.	17.	32.0	1–5	10	30
					5–10	45	90
					10–15	60	85
					15–20	40	15
					20–25	55	
					25–30	10	
7	2.03	2.5	1.6	32.5	1–5	480	360

Calculation of total live load

The total live load is the sum of the static live load, which is the load produced by the weight of all spectators sitting on the beam, plus the amplitude of the dynamic live load. Within this paper the latter is the static load that produces approximately the same deflected shape of the beam as the rhythmic, impulsive forces generated by the audience. Dynamic live loads for each of the seven songs that produced large amplitude vibrations were calculated only for beam 7, since horizontal accelerations were not recorded on the other two beams.

Static live load

The static live load for beam 7 was estimated to be 1.5 kN/m^2 (32 psf). This is the load obtained by assuming that all seats and aisle space on the beam were occupied and that the average weight per spectator was 68 kg (140 lb).

Dynamic live load

Because the monitored section of the lower stands was completely full of spectators, the rhythmic, impulsive forces produced by the audience during foot stamping sessions were assumed to be uniformly distributed along the beam. As a result, dynamic live loads were calculated by assuming that the static loads were also uniformly distributed along beam 7. The amplitude of each uniformly distributed static load (dynamic live

TABLE 3. Calculated dynamic live loads for beam 7

Song	Stamping frequency, Hz	Maximum peak mid-span displacement: Vertical, mm	Maximum peak mid-span displacement: Horizontal, mm	Calculated dynamic live load: Vertical, N/m^2	Calculated dynamic live load: Horizontal, N/m^2
1	2.60	0.59	0.38	73	27
2	2.83	0.71	0.46	87	37
3	2.50	4.8	3.2	570	270
4	2.47	5.5	3.8	650	340
5	2.44	5.8	3.8	710	310
6	2.37	12.	7.4	1500	540
7	2.03	1.5	0.96	190	75

load) was determined from the maximum peak dynamic midspan deflection, assuming that beam 7 was simply supported by the concrete shear walls, that torsional bracing prevented the beam from twisting, and that the dynamic shape of the deflected beam about a principal centroidal axis was

$$[1] \quad d(x,t) \simeq \frac{\mathrm{UDL}x}{24EI}(L^3 - 2Lx^2 + x^3) \sin 2\pi pt$$

where $d(x,t)$ is the deflected shape in millimetres (in.), UDL is the amplitude of the uniformly distributed dynamic live load in kN/m (lb/in.), E is the modulus of elasticity in MPa (psi), I is the principal moment of inertia in mm^4 ($in.^4$), L is the span in millimetres (in.), and p is the stamping/clapping frequency in Hz.

From [1] the uniformly distributed load required to produce a maximum peak mid-span deflection, δ about a principal centroidal axis is

$$[2] \quad \mathrm{UDL} = \frac{384(EI)}{5L^4}\delta$$

Maximum peak mid-span deflections were calculated from maximum peak mid-span accelerations, assuming harmonic motion at frequency p. Principal moments of inertia (Fig. 7) and a modulus of elasticity of 3.7×10^4 MPa (5.3×10^6 psi) were used in [2]. Vertical and horizontal dynamic live loads (Table 3) were obtained by transforming the dynamic live loads calculated for the principal centroidal axes from [2] to the vertical and horizontal axes. These loads are probably about 10% less than the maxima that would have been obtained for each song in this section of the lower stands had horizontal accelerations been recorded on beams 5 and 6.

The maximum dynamic live loads for beam 7 were obtained for song 6: 1.5 kN/m^2 (32 psf) in the vertical direction and 0.54 kN/m^2 (11 psf) in the horizontal direction. The maximum total vertical live load for beam 7 was therefore 3.0 kN/m^2 (64 psf), which is considerably below the 4.8 kN/m^2 (100 psf) design live load.

Discussion and summary

Of approximately 25 songs played during a 3 h rock concert about 12 were accompanied by hand clapping and foot stamping, and 7 of the 12 produced peak vertical harmonic accelerations in the stands that continuously exceeded 1% g for at least 30 s. Each of the 12 songs had a stamping/clapping frequency between 2 and 3 Hz. The average, and what appears to be the frequency most susceptible to audience participation, was 2.5 Hz.

During song 6 resonance of the stands occurred. Maximum peak accelerations of 0.30 g in the vertical direction and 0.17 g in the horizontal direction at a frequency of 2.37 Hz were recorded. The calculated vertical dynamic live load during this song was 1.5 kN/m^2 (32 psf), which is the same as the estimated static live load. Under existing occupancy conditions within the arena 1.5 kN/m^2 (32 psf) is probably the maximum static live load for this floor system, since the number of seated spectators per beam is effectively controlled by the presence of seats with arm rests and backs. As a result, it seems very unlikely that the total live load will ever exceed the design live load of 4.8 kN/m^2 (100 psf); resonant accelerations would have to double for this to occur.

For songs 3–6, vibrations produced by the audience could be readily seen since maximum peak-to-peak resultant displacements were 12 mm (0.5 in.) or greater. Only at these extremely large dynamic amplitudes did the audience appear to be aware of the vibrations to which they were being subjected.

Acknowledgement

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