Avoiding
Damage, Distress, and Disappointment
in Concrete Structures

Minnesota Concrete Council
Virtual Meeting
February 23, 2021

by
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Learning Objectives

- Understand better why not all projects go well
- Know common reasons for cracking in concrete floors and ways to mitigate
- Be aware of criteria for evaluating decorative concrete
- Identify common tolerance problems

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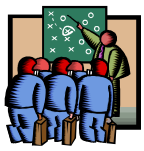
Audience and Goals

- Project Team
  - Specifier
  - Contractor
  - Inspector
- Technical Focus
  - Understand distress mechanism
  - Mitigation



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Presentation Content

- Notable Structural Failures
- Common Problems
- Excessive Slab Cracking
- Exposed Concrete
- Tolerances

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Problems

- Inadequate strength
- Excessive deflection
- Low durability
- Poor appearance
- Tolerances
- Extreme loading
- Neglect/Abuse
- Unrealistic expectations

Joplin 2011

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Strength and Serviceability
International Building Code (IBC)

SECTION 1604
GENERAL DESIGN REQUIREMENTS

1604.2 Strength. Buildings and *other structures*, and parts thereof, shall be designed and constructed to support safely the *factored loads* in load combinations defined in this code without exceeding the appropriate strength *limit states* for the materials of construction.

1604.3 Serviceability. Structural systems and members thereof shall be designed to have adequate stiffness to limit deflections as indicated in Table 1604.3.

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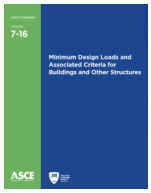
Strength, Stiffness, and Serviceability
ASCE 7



1.3 BASIC REQUIREMENTS

1.3.1 Strength and Stiffness. Buildings and other structures, and all parts thereof, shall be designed and constructed with adequate strength and stiffness to provide structural stability, protect nonstructural components and systems, and meet the serviceability requirements of Section 1.3.2.

1.3.2 Serviceability. Structural systems, and members thereof, shall be designed under service loads to have adequate stiffness to limit deflections, lateral drift, vibration, or any other deformations that adversely affect the intended use and performance of buildings and other structures based on requirements set forth in the applicable codes and standards, or as specified in the project design criteria.

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Notable Structural Failures

Date	Project Name	Location	Fatalities
1940	Tacoma Narrows Bridge	Tacoma, WA	0
1973	Skyline Plaza Apartments	Fairfax, VA	14
1978	Cooling Tower	Willow Island, WV	51
1981	Hyatt Regency Walkways	Kansas City, MO	113
1987	L'Ambiance Apartments	Bridgeport, CT	28
2006	I-90 Tunnel Ceiling	Boston, MA	1
2007	IH-35W Bridge	Minneapolis, MN	13
2018	Florida Int'l University Bridge	Miami, FL	6

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Skyline Plaza Apartments

Premature Shoring Removal

(NBS/NIST)

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Willow Island Cooling Tower
Construction Loads on Prior Placement

(NBS/NIST)

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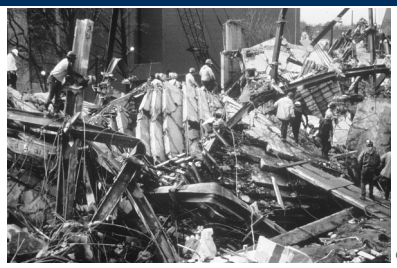
L'Ambiance Plaza
Lift Slab Shearhead Deformation



(NBS/NIST)

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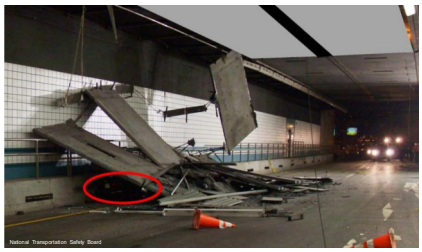
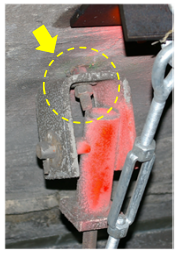
I-90 Tunnel Ceiling Collapse
Post-installed Anchor Pullout





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NTSB Investigation Findings

- Anchor displacement
- Extensive voiding
- Low anchor load capacity
- Reduced capacity due to:
  - No cleaning
  - Poor mixing
  - Voiding

Recommendations to:

- AASHTO
- ACI
- ASCE
- FHWA
- ICC
- Manufacturer
- Researchers
- Educators

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Adhesive Anchor Installation Research

- Poor performance due to:
  - Sustained load
  - Incomplete adhesive encapsulation
- Led to:
  - Training
  - Code changes

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Resulting Code Changes

- ACI 318-11, Appendix D

D.9.2.2 — Installation of adhesive anchors horizontally or upwardly inclined to support sustained tension loads shall be performed by personnel certified by an applicable certification program. Certification shall include written and performance tests in accordance with the ACI/CRSI Adhesive Anchor Installer Certification program, or equivalent.

D.9.2.4 — Adhesive anchors installed in horizontal or upwardly inclined orientations to resist sustained tension loads shall be continuously inspected during installation by an inspector specially approved for that purpose by the building official. The special inspector shall furnish a report to the licensed design professional and building official that the work covered by the

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IBC 2021 Criteria
Chapter 17

TABLE 1705.3
REQUIRED SPECIAL INSPECTIONS AND TESTS OF CONCRETE CONSTRUCTION

TYPE	CONTINUOUS SPECIAL INSPECTION	PERIODIC SPECIAL INSPECTION
4. Inspect anchors post-installed in hardened concrete members.[b]		
a. Adhesive anchors installed in horizontally or upwardly inclined orientations to resist sustained tension loads.	X	—
b. Mechanical anchors and adhesive anchors not defined in 4.a.	—	X

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Less Catastrophic Problem
Slab Cracking

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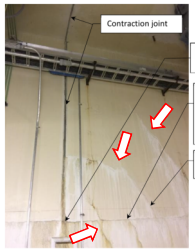
Less Catastrophic Problem
Water Leakage Tank Wall



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Force and Stress

More certain

Less certain

- Loads
  - Dead – self weight and building finishes
  - Live – occupancy
  - Snow
  - Wind
  - Seismic
- Soil movement – heave and settlement
- Volume change – creep, shrinkage, and temperature

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Historical Review
Investigations Conducted by M. Lee[1]

Age (Yrs)	FACILITY TYPE	MATERIAL	AFFECTED ITEM	SOURCE	CAUSE
10+	Retail	Concrete (tilt-up)	Panel Connection	Volume Change	Both
10+	School	Concrete SOG	Floor Slab	Soil Movement	Both
1	Hotel	Concrete CIP	Retaining Wall	Lateral Pressure	TBD
10+	School	Concrete CIP	Grade Beams; Slab	Soil Movement	Construction
2	Garage 5	Precast	DT Connection	Volume Change	Design
2	Garage	Precast	DT Connection	Volume Change	Design
8	Medical	Concrete Foundation	Floor Slab	Heave	Design
1	Retail	Concrete SOG	Floor Slab	Heave	Design
10+	School	Cold-formed Steel	Parapet	Wind	Construction
1	Multi-family 10	Wood	Entire Structure	Volume Change	Both

Note 1: Based on 30 consecutive assignments; survey date 9/2016; only 10 shown for clarity

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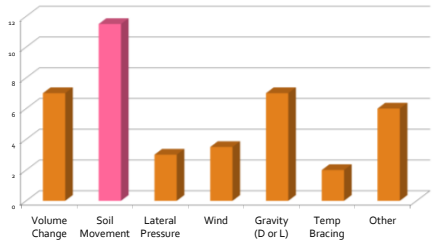
Primary Cause of Problem



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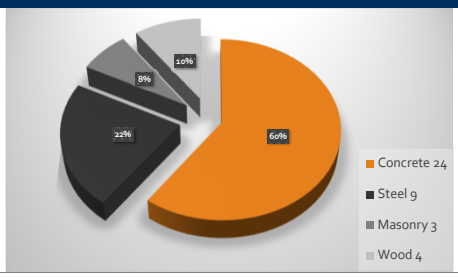
Primary Material



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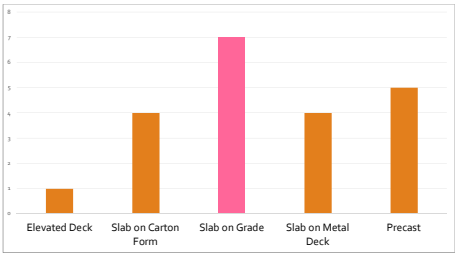
Type of Concrete



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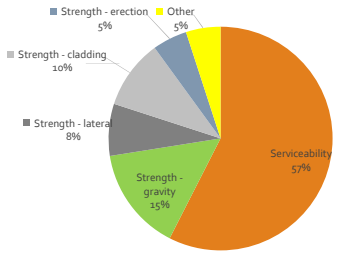
Strength or Serviceability?



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Restrained Volume Change
ASCE 7

1.3.4 Self-Straining Forces and Effects. Provision shall be made for anticipated self-straining forces and effects arising from differential settlements of foundations and from restrained dimensional changes caused by temperature, moisture, shrinkage, creep, and similar effects.

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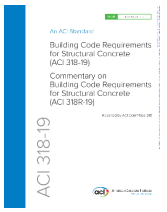
Restrained Volume Change
ACI 318

5.2—General

5.2.1 Loads shall include self-weight; applied loads; and effects of prestressing, earthquakes, restraint of volume change, and differential settlement.

5.3.6 The structural effects of forces due to restraint of volume change and differential settlement T shall be considered in combination with other loads if the effects of T can adversely affect structural safety or performance.

T = cumulative effects of service temperature, creep, shrinkage, differential settlement, and shrinkage-compensating concrete



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Approximate Length Change

- Shrinkage Strain: 700 x E-06 in/in
- Coef. Thermal Expansion: 6 x E-06 in/in/F

For 100 ft long slab, total shortening due to shrinkage on order of 3/4 inch

For same slab, total length change over 100-degree F temperature range also on order of 3/4 inch

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ACI 318 Shrinkage &Temperature Steel

Code:

7.6.4.1 Reinforcement shall be provided to resist shrinkage and temperature stresses in accordance with 24.4.

24.4.3.2 The ratio of deformed shrinkage and temperature reinforcement area to gross concrete area shall be greater than or equal to 0.0018.

Commentary:

If crack width or leakage prevention is a design limit state, refer to ACI 224R or ACI 350 for recommended reinforcement ratios.

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Inadequacy of ACI 318 S&T Steel to Control Cracking

The minimum amount and spacing of reinforcement to be used in structural floors, roof slabs, and walls for control of temperature and shrinkage cracking is given in ACI 318 or in ACI 350R. The minimum-reinforcement percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.

Refers to unjointed slabs. From ACI 224R-01, 3.5.2

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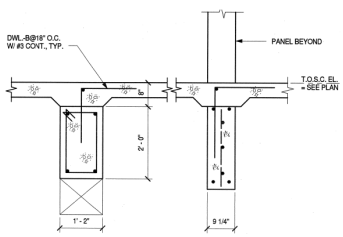
Slabs on Ground Drying Shrinkage Common Sources of Restraint

- Grade beams
- Walls
- Columns
- Piers
- Trenches/drains
- Elevator pits
- Excessive rebar crossing contraction joints



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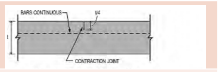
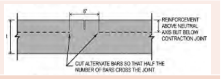
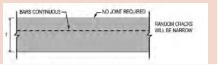
ACI 224.4R
Reinforcing amount for slabs on ground

Reinforcement Classification	Amount of Reinforcing Steel	Excerpt from ACI 224.4R, Fig. 8.2a
Light	< 0.10% (i.e., <0.0010 Ag)	
Moderate	0.18 to 0.20% (close to ACI 318 0.0018)	
Heavy	> 0.50%	

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Percentage of Reinforcing Steel
for Various Bar Sizes and Spacings (5" thick SOG)

Reinforcement Design	Percentage (%)
#3 at 18"	0.12
#3 at 16"	0.13
#3 at 12"	0.18 *
#4 at 16"	0.25 *
#4 at 12"	0.33 **
#4 at 9"	0.44**

* To improve effectiveness of CJs and mitigate cracking, alternate bars should be cut at CJ
** Too much steel crossing CJ to allow opening and not enough to keep cracks tight

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Slabs on Ground Crack Mitigation
Favorable Practices

- Lowest practical slump and largest aggregate size
- Retain moisture within concrete as long as possible
- Aggressively address low humidity and high wind speed
- Protect early-age concrete from temperature gradients
- Saw-cut joints at earliest time possible

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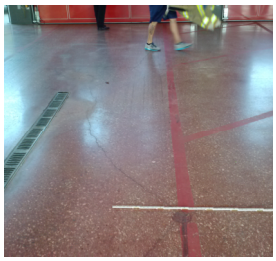
Decorative Concrete

- Floors
  - Stained
  - Integrally Colored
  - Polished
- Walls
  - As cast
  - Sandblasted



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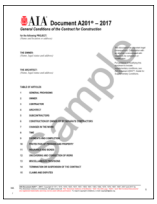
Decorative Concrete
AIA A201, *General Conditions*

4.2.13:

"The Architect's decisions on matters related to aesthetic effect will be final if consistent with the intent expressed on the Contract Documents."



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Decorative Concrete

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Repairing Non-compliant Concrete
ACI 301-20

1.8.1.3 Repair rejected concrete Work by removing and replacing or by additional construction to strengthen or otherwise satisfy project requirement as directed by Architect/Engineer. To bring rejected Work into compliance, use repair methods that meet applicable requirements for function, durability, dimensional tolerances, and appearance as determined by Architect/Engineer.

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Decorative Concrete
Partial Replacement

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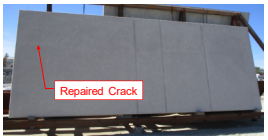
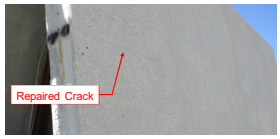
Sample Specification Language
Repaired Wall Panels

"Panels having non-structural damage may be erected provided damage can be repaired to the Owner's Representative's satisfaction. Repair surfaces must be repaired in a manner to be undetectable from ground level."





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Decorative Concrete
PCI *Manual for … Architectural Precast Concrete (MNL117)*

"The finished surface shall have no obvious imperfections other than *minimal* color and texture variations from the approved samples or evidence of repairs when viewed in good typical daylight illumination with the unaided naked eye consistent with the viewing distance on the structure, but *not less than 20 ft*."

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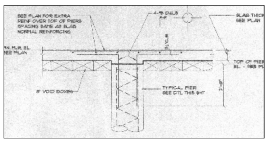
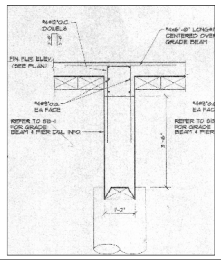
Slab Top Reinforcing Steel Placement
Structural Slabs



16. MINIMUM CONCRETE COVER OVER REINFORCING BARS SHALL BE:
3" AT FOUNDATIONS CAST AGAINST SOIL
2" AT FACES OF WALLS EXPOSED TO WEATHER OR SOIL.
1-1/2" AT COLUMNS AND BEAMS.
3/4" AT STRUCTURAL SLABS AND WALLS NOT EXPOSED TO WEATHER.

3.3.2 *Placing*

3.3.2.1 *Tolerances*—Place, support, and fasten reinforcement to maintain its location during concrete placement in accordance with Contract Documents.



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Stadium No. 2
Rebar placement within slab depth

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Slab Reinforcing Steel Placement Structural Slabs

- Expect top steel clearance to exceed specified 3/4"
- Checking rebar top cover is critical for strength and crack control
- Alert project team of potential for cracks

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Other Tolerance Concerns

- Elevator shaft size and plumb
- Floor slab flatness and levelness
- Slab edge interface with curtain walls
- Time sensitive measurements:
  - Flatness and levelness within 72 hrs
  - Before shoring removal
  - Before post-tensioning application

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CASE HISTORY

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Football Stadium
Cracking in Pan Joist Slab

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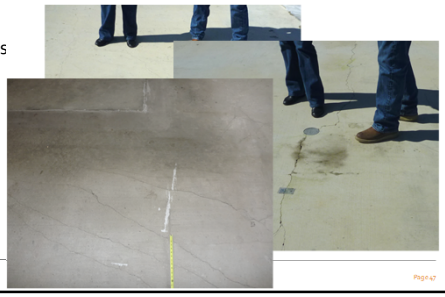
Football Stadium Pan Joist Slab
Excessive Cracking

- Skip joist framing
- 4.5" slab / 20" pans
- Expansion joints
- Basement

- Built 2013
- Closed 2014
- Repaired 2015
- Opened late 2015



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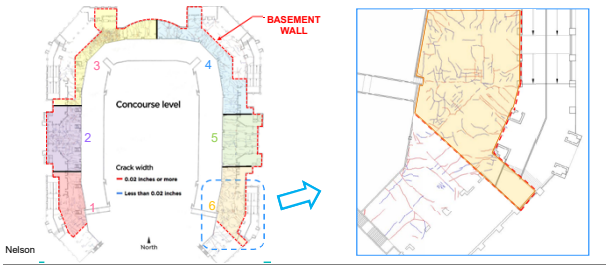
Football Stadium Pan Joist Slab
Crack Map



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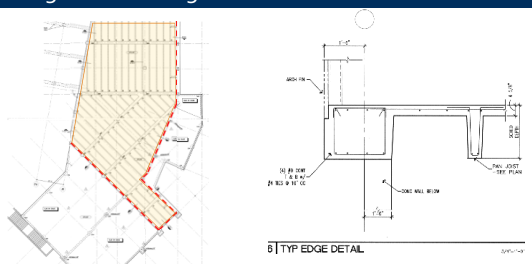
Football Stadium Pan Joist Slab
Framing Plan and Edge Detail at Basement Wall



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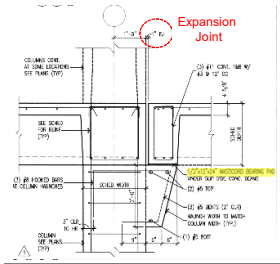
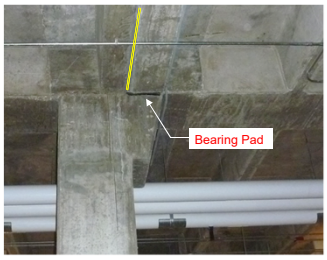
Football Stadium Pan Joist Slab
Expansion Joint at Shared Column





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Football Stadium Pan Joist Slab
Takeaways

- Irregular plan geometry prevented effective layout of EJs
- Double columns would have provided better isolation at EJs
- Pan joist framing susceptible to cracking
- Ineffective curing led to increased shrinkage cracking
- Basement walls restrained deck shrinkage

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CLOSING

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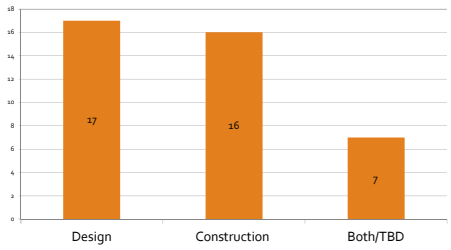
Design or Construction "Error"?



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Risk of Death[1]

Activity	Deaths per Million People per Hour Exposure	Hours Exposure per Year	Annual Risk of Death (%)
Automobile Travel	1.04	340	0.036
Swimming	3.50	20	0.007
Collapse – construction worker		-	0.003
Collapse – public		-	0.00002

[1] National Research Council of Canada CBD-147

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Summary

- All project team members must do their part
- Respect volume change
- Set expectations within project team
- Relatively low rate of structural failures shows system generally works well
- Repeated instances of serviceability problems shows room for improvement

Questions?